OPTIMIZATION OF BIOGAS PRODUCTION FROM THE BLEND OF CASSAVA, YAM, AND POTATO PEELS

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CERTIFICATION

This is to certify that this research project was carried out by **IGHOSOTU CHRISTOPHER ONOME** with matriculation number **ENG2002043** in the Department of Chemical Engineering at the University of Benin, Benin City, Edo State, Nigeria.

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DEDICATION

This project work is dedicated to GOD ALMIGHTY, the source of my life and sustenance, who has graciously guided me throughout my academic journey. I also dedicate this work to the Blessed Virgin Mary for her constant intercession and the graces received through her during my academic journey.

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ABSTRACT

This study aim to optimize biogas production from the co-digestion of cassava, yam, and potato peels with cow dung as inoculum, addressing the dual challenges of agricultural waste management and renewable energy generation in Nigeria. The research sought to determine the most effective substrate mixing ratios and associated process conditions that enhance biogas yield and methane content while providing sustainable solutions for converting abundant agricultural residues into clean energy.

The optimization was conducted through batch anaerobic digestion at laboratory scale using a simplex lattice mixture design approach. The study involved three consecutive batches with four experimental runs each, totaling twelve runs over an 8-day hydraulic retention time per batch. Fresh cattle rumen was obtained from Abattoir Oluku, while cassava peels were sourced from the Ogba community, and yam and potato peels were collected from Ekosodin, Ugbowo community, all in Edo State, Nigeria. The feedstocks underwent systematic pretreatment including washing, oven drying at 100 - 130°C for 18 hours, grinding using mortar and pestle followed by manual hand grinding, and sieving through 500-micro mesh to achieve uniform particle size. Proximate analysis determine moisture content, ash content, volatile matter, and fixed carbon, while ultimate analysis using Energy – Dispersive X-ray Fluorescence (EDXRF) spectrometry establish elemental composition including carbon-nitrogen ratios. A fixed mass of 50g cow dung dissolved in 150ml water served as inoculum for each experimental run. The biogas volume was measured using the water displacement method with Buchner flask setups, and statistical analysis was performed using Response Surface Methodology and Analysis of Variance (ANOVA) through Design Expert software to evaluate model significance and develop predictive equations.

The results revealed that pure yam peel produced the highest biogas yield of 180 ml/50g.week with excellent methane concentration of 88.2%, significantly outperforming cassava peel (98.4 ml/50g.week, 86.7% CH_4) and potato peel (70 ml/50g.week, 82.5% CH_4). The binary blend of yam and cassava peels demonstrated synergistic effects with 147.5 ml/50g.week yield and 87.9% methane content, while yam-potato combinations exhibited strong antagonistic interactions producing only 25 ml/50g.week. Statistical validation confirmed excellent model fit with R^2 values of 0.9982 for biogas yield (Special Quartic model) and 0.9523 for methane concentration (Quadratic model), both significant at $p < 0.001$. The cow dung characterization revealed substantial nutrient content including calcium (36.20%), potassium (14.65%), phosphorus (9.62%), and nitrogen (3.89%), confirming its suitability as an effective inoculum. These findings demonstrate that strategic substrate blending, particularly yam-cassava combinations, can optimize biogas production from agricultural waste while providing practical guidelines for small-scale biogas systems in resource-limited settings.

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CHAPTER ONE

INTRODUCTION

1.1. BACKGROUND OF STUDY

Energy serves as a cornerstone of economic growth and social development, yet its availability and reliability remain a persistent challenge in developing nations. The Nigerian energy landscape is characterized by substantial reliance on fossil fuels, with natural gas accounting for approximately 79.5% of electricity generation in 2023, followed by hydroelectric power at about 20.4%, while traditional biomass and waste contribute around 73.5% to the country's total primary energy consumption as of 2018, reflecting the reality that many Nigerians, particularly in rural areas, continue to rely on traditional energy sources for their daily needs (John et al., 2025).

Nigeria, being Africa's most populous nation with over 216 million people and an annual population growth rate of 3.2%, confronts an inconsistent energy crisis that basically hinders its economic growth and development despite being endowed with vast natural resources, including significant reserves of oil and natural gas (Umar et al., 2024). This heavy dependence on conventional energy sources has shaped the nation's energy infrastructure and economic trajectory for decades, creating multiple interconnected challenges including environmental pollution, energy insecurity, and economic vulnerabilities (H. Amadi et al., n.d.).

Fossil fuels, majorly oil and gas, constitute a significant portion of Nigeria's total goods and services exports, with fossil fuel exports generating substantial foreign exchange earnings and serving as a vital contributor to the government budget, thereby making the country's economy closely tied to the oil industry and vulnerable to global oil market fluctuations and external macroeconomic conditions. The country's over-reliance on fossil fuels has led to increased carbon dioxide emissions and environmental degradation, further compounding the sustainability challenges facing the nation. The inadequacy of the national grid has forced millions of households and businesses to seek alternative power solutions and rely on off-grid petrol and diesel-powered generators, often at considerable expense, further entrenching fossil fuel dependence and hampering socio-economic development while intensifying the gap between energy potential and actual supply. However, Nigeria possesses considerable high renewable energy potential across multiple sources, with solar energy offering an average daily radiation of 5.5 kWh/m^2 and benefiting from the country's geographical location near the equator which ensures consistent solar irradiation throughout the year, making it a leading candidate for integration into the grid network (John et al., 2025).

Hydropower currently contributes about 29% of the national energy mix potential and can be further expanded through the development of additional dam projects and the optimization of existing facilities, while wind energy, though less developed, holds promise in northern Nigeria where wind speeds are sufficient for large-scale production (John et al., 2025). Projections indicate that by 2050, renewable sources could supply nearly 60% of the nation's energy demand, significantly reducing dependence on natural gas and oil, representing a fundamental shift in the country's energy paradigm that would address the urgent need for expanded capacity and improved distribution systems created by rapid population growth (John et al., 2025).

Bioenergy represents a particularly attractive pathway within this transition, as it can be obtained from any biologically decomposable organic matter such as plants or animals, including terrestrial plants, aquatic plants, wastes from wood processing, organic fractions of municipal solid wastes, animal manures, crop residues, sewage sludge, and debris from forestry. Anaerobic digestion technology has received widespread global acceptance and appears to have strong prospects for sustainable energy production, particularly in converting the abundantly generated agricultural wastes in Nigeria such as peels from potatoes, yam, cassava, and similar crops from processing for food and industrial uses that are currently disposed of indiscriminately, creating piles of rotting waste with foul odor and constituting nuisance with negative environmental impact into biogas (Opurum et al., 2021). Biogas is a clean renewable energy consisting of a mixture of methane with percentage over 60% and carbon dioxide, where methane serves as the main combustible gas responsible for energy content (Kumar et al., n.d.).

Biogas systems provide dual benefits by serving as a fuel substitute for firewood, dung, agricultural residues, petrol, diesel, and electricity for cooking and lighting while simultaneously producing residue organic waste after anaerobic digestion that has highly superior nutrient qualities over usual organic fertilizer in the form of Ammonia (Kumar et al., n.d.). As compared to other waste treatment technologies, biogas plants emit fewer greenhouse gases into the atmosphere, minimize the use of nonrenewable fuels including wood and charcoal, indirectly help conserve forests and biodiversity resources, minimize groundwater pollution, solve waste disposal problems and associated costs, and reduce greenhouse gas emissions by moderating methane emissions, thereby exemplifying a circular green economy approach that addresses Nigeria's energy transition challenges through waste conversion into bioenergy with broader impacts beyond clean energy production (Kelif Ibro et al., 2024a).

1.2. STATEMENT OF THE RESEARCH PROBLEM

The escalating production of root and tuber crops in Nigeria particularly cassava, yam, and potato alongside intensive livestock farming has led to the generation of substantial quantities of peels, processing residues, and animal manure that pose serious environmental and public health challenges. These dual waste streams, both rich in organic matter, are often disposed of indiscriminately in rural and peri-urban areas, where they undergo uncontrolled fermentation and putrefaction, emitting foul odors and contributing to soil and water contamination through nutrient leaching and pathogen dissemination. Agricultural residues such as cassava peels, though rich in cellulose and hemicellulose, have limited application as livestock feed due to hydrocyanic acid content, while cow dung and other animal manures, despite their high nutrient content and microbial populations, accumulate around farms and homesteads, creating sanitation hazards and contributing to greenhouse gas emissions. Anaerobic co-digestion of blended substrates combining yam peel, cassava peel, and potato peel with cow dung offers a synergistic solution: the carbon-rich plant residues complement the nitrogen rich animal manure, enhancing microbial activity and process stability while simultaneously providing sustainable waste management and generating biogas as a renewable energy source and nutrient-rich digestate for soil amendment.

1.3. AIM AND OBJECTIVES

1.3.1. Aim

The aim of this project is to Optimize biogas production from the blend of Cassava, yam, and potato peels.

1.3.2. Objectives

1. Feed stock collection.
2. Pretreatment of the feed stocks.
3. Feed stock Characterization.
4. Carry out the experiment based on the experimental design.
5. Determine the optimal blend ratio of the feed stock to optimize the volume, methane concentration, and CO_2/H_2S concentration.

1.4. SCOPE OF THE STUDY

This study centers on the optimization of biogas production via the co-digestion of selected agricultural waste substrates specifically, cassava peels, yam peels, and potato peels blended with cow dung, with all experiments conducted at a controlled laboratory scale. The investigation adopts a systematic batch anaerobic digestion methodology, structured across three consecutive batches to ensure reproducibility and progressive refinement. Each batch operates with a fixed 8-day hydraulic retention time and incorporates four distinct experimental runs, leading to a comprehensive total of 12 runs throughout the entire study duration. Through this structured design, the research specifically aims to determine the most effective substrate mixing ratios and associated process conditions that enhance biogas yield and methane content. The overall scope remains deliberately constrained to align with the practical constraints and feasible timeline of an undergraduate-level project.

1.5. SIGNIFICANCE OF STUDY

This study addresses the urgent need for sustainable waste management and renewable energy solutions by optimizing biogas production from agricultural waste materials that are abundantly available but underutilized in many developing regions. The study fills an important gap in understanding the co-digestion dynamics of cassava, yam, and potato peels with cow dung, as systematic optimization of their blends remains limited despite individual substrates being studied. This research advances knowledge on substrate interactions, nutrient balancing, and optimal mixing ratios that enhance microbial activity during anaerobic digestion, contributing empirical data to the scientific literature on multi-substrate co-digestion. The optimized blend ratios and process parameters developed offer practical solutions for improving biogas yield and digestion stability, providing actionable guidelines for operators of small-scale biogas systems through cost-effective and accessible methods suitable for household and community-level digesters where technical expertise and resources may be limited. Converting abundant agricultural peels into biogas reduces organic waste accumulation and associated pollution while generating clean cooking fuel, decreasing reliance on firewood and fossil fuels and thereby mitigating greenhouse gas emissions and deforestation. Rural farmers and households gain opportunities for income generation through waste valorization and reduced energy costs, as the study supports local circular economy principles by turning waste into valuable energy resources. The findings will benefit smallholder farmers, rural households, biogas plant operators, environmental policymakers, and renewable energy researchers, while contributing to broader goals of energy security, climate change mitigation, and sustainable development through reduction of agricultural waste, increased biogas yield, enhanced energy security, cost-effective technology deployment, support for climate action, and contribution to local livelihoods and sustainable circular economy practices.

CHAPTER TWO

LITERATURE REVIEW

2.1 ENERGY

Energy is defined as the capacity to perform work, and it is integral to our daily activities, contributing to both mental and physical development. It is essential for powering residential infrastructure, fueling transportation, driving industrial production, and sustaining biological functions. The absence of energy would significantly alter our current way of life. Furthermore, energy is pivotal for economic development, technological advancement, and the enhancement of overall quality of life. It is important to ensure that energy production and consumption are aligned with environmental and sustainability considerations to safeguard the planet for future generations(Makiya et al., 2024).

Energy manifests in various forms, including thermal, mechanical, electrical, chemical, hydropower, and nuclear. All energy can be categorized into two primary types: kinetic and potential. Kinetic energy pertains to motion, exemplified by a rock descending a hill, wind moving through trees, water cascading over a dam, and a cyclist riding a bicycle. Potential energy, on the other hand, is the energy possessed by an object or system due to its position relative to another object or system and the forces acting between them. Illustrative examples include a rock positioned at the summit of a hill and water stored behind a dam. Certain forms of energy represent a combination of kinetic and potential energy. Chemical energy, a variant of potential energy, denotes the potential of a chemical substance to undergo a reaction and transform other substances. Instances of this include the energy contained in the food consumed and the gasoline used in vehicles(Freedman et al., 2024).

Energy plays a crucial role in our daily lives and is essential for various forms of development. It is required for numerous household activities, including the use of electricity, heating residences, cooking, operating vehicles, and even agricultural practices. In the absence of energy, the execution of these tasks would be unfeasible (Diako et al., n.d.).

The provision of energy is crucial to the socioeconomic development and growth of a nation. As a traded commodity, energy has the potential to generate revenue that supports governmental projects and programs, thereby playing a significant role in international diplomacy. Energy is indispensable for political, security, and diplomatic endeavors, as well as for facilitating the production of goods and services across various sectors, including transportation, agriculture, industry, healthcare, and education. For nations to achieve rapid and sustained socioeconomic growth, access to high-quality infrastructure services, particularly electricity, is imperative.

2.2 ENERGY SECTOR IN NIGERIA

Nigeria possesses a substantial array of energy resources capable of fulfilling its present and future developmental requirements. The nation is endowed with a diverse range of energy resources, including coal, natural gas, tar sands, and crude oil, all of which are of high quality. Crude oil alone constitutes over 90% of Nigeria's economic activity. With an estimated resource of 36 million barrels, equivalent to approximately 4.9 billion tonnes of oil equivalent (toe), Nigeria was ranked as the tenth largest crude oil producer globally in 2006. The country's natural gas reserves are estimated at 5210 billion m^3 (187 trillion SCF) as of 2006, surpassing the abundance of oil. These reserves include both associated and non-associated gas, positioning Nigeria among the top ten nations worldwide with the largest gas reserves. Furthermore, Nigeria has 1.52 billion tonnes of coal and lignite, in addition to 4.1 billion tonnes of tar sands(H. N. Amadi et al., n.d.).

Addressing Nigeria's electricity crisis and enhancing its low access rate necessitates a multifaceted strategy that addresses various challenges within the power sector. Essential measures include expanding generation capacity, improving transmission and distribution infrastructure, and implementing smart grid technology. Investment in renewable energy sources such as solar, wind, and waste biomass can diversify the energy mix, thereby reducing dependence on gas and diesel generators (Umar et al., 2024). Approximately 70% of Nigeria's primary energy needs are currently met by fuelwood, yet only 40% of the population has access to electricity. This situation contrasts sharply with countries like South Africa, where, despite a significantly smaller population, there is a much higher electricity capacity. Nigeria, which currently relies on fossil fuels such as oil (33%), coal (27%), and natural gas (25%) for most of its energy, is on the verge of a substantial transition towards sustainable and renewable energy sources.

The nation is well-equipped to tackle its energy challenges due to its abundant renewable resources, including solar, wind, hydropower, and biomass. The potential for solar energy is vast, with estimates suggesting that deploying solar photovoltaic (PV) panels on just 0.01% of Nigeria's land could generate energy equivalent to millions of tons of oil. Wind energy also presents significant opportunities, particularly in the coastal and northern regions, which experience favorable wind speeds. Additionally, the hydropower sector, which already contributes to the national grid, possesses considerable undeveloped potential in Nigeria's rivers and waterways. Implementing small to medium-scale hydroelectric projects could significantly enhance energy supply, particularly in off-grid areas (Adeshina et al., n.d.).

2.3 TYPES OF ENERGY

Among these, certain sources are classified as renewable - due to their ability to be replenished at a rate that exceeds their consumption; and non-renewable - characterized by their consumption rate surpassing the rate at which they are naturally replenished (Gil Bravo et al., 2024).

2.3.1 Non-Renewable Energy

Nonrenewable energy is derived from sources that are not rapidly replenished. This category encompasses energy generated from nuclear power and fossil fuels, including coal, oil, natural gas, and lignite. These resources require millions of years to form and are extracted from the earth. The production of nonrenewable energy depends upon the availability of these resources, which are finite and may be depleted over time (Mekuye et al., 2024).

2.3.1.1 Fossil Fuels

Fuel is a substance that provides energy in the form of heat, light, or electricity. Fossil fuels are hydrocarbon-based materials derived from the decomposed remains of ancient plants and animals, formed over hundreds of millions of years through exposure to heat and pressure within the Earth's crust. Once extracted and utilized, fossil fuels are non-renewable. These fuels produce carbon-rich deposits that are combusted for energy (Mekuye et al., 2024). These fuels play a crucial role in the global economy, supplying a significant portion of the energy utilized daily. Fossil fuels are located deep within the Earth's crust and are extracted through methods such as mining and drilling (Alagoz E. & Alghawi Y., 2024). The primary types of fossil fuels include coal, oil, and natural gas.

1. **Coal:** Coal is a combustible sedimentary rock that is either black or brownish black, containing a high concentration of carbon and hydrocarbons. It is categorized into four primary types based on the carbon content and the heat energy it can generate: anthracite, bituminous, subbituminous, and lignite (Freedman et al., 2024). Despite its long-standing use, coal is recognized for emitting substantial amounts of carbon dioxide upon combustion, a primary contributor to climate change. Coal mining process can adversely have impact on the environment by destroying habitats and contaminating water sources(Alagoz E. & Alghawi Y., 2024).

2. **Crude oil:** Crude oil is composed of hydrocarbons, which are molecules containing hydrogen and carbon in various configurations, including linear chains, branched chains, and rings. These hydrocarbons are energy-dense, and numerous products derived from crude oil, such as gasoline, diesel fuel, and paraffin wax, exploit this energy (Freedman et al., 2024). Crude oil is a vital resource employed for power generation, heating, and other applications. Despite environmental concerns regarding its role in greenhouse gas emissions and climate change, crude oil remains integral to daily life, with numerous industries reliant on it for transportation and fuel production. (Alagoz E. & Alghawi Y., 2024).
3. **Natural gas:** It is a gaseous fuel gotten from the remains of extinct plants and animals (Alagoz E. & Alghawi Y., 2024). Natural gas is mainly made up of methane (CH4). When natural gas is extracted from the ground, it often contains other gases like butane and propane. These gases are separated and cleaned at a processing plant. Once separated, these by-products can be used in various ways, such as using propane for cooking on gas grills. Sometimes, the natural gas from a well also contains liquid hydrocarbons and other gases. This is called wet natural gas. Natural gas is separated from these components near the well or at a processing plant. When the gas is just methane, it is called dry natural gas and is sent through pipelines to a local distribution company and, eventually, to the consumer (Freedman et al., 2024).

2.3.1.2 Nuclear Energy

Nuclear energy is produced through the processes of fission and fusion. Fission involves the division of atomic nuclei into two smaller atoms, whereas fusion involves the combination of two hydrogen atoms to form a helium atom. This process requires minimal uranium fuel to generate a significant amount of energy without emitting carbon dioxide or other greenhouse gases. The energy required to separate a particle and disperse all particles in a system is referred to as binding energy. The release of energy from the decay of certain atomic nuclei and isotopes is known as radioactivity. A nuclear power plant generates thermal energy by breaking the bonds of uranium, plutonium, or thorium in atomic nuclei or by splitting uranium atoms to produce energy (Mekuye et al., 2024). The primary environmental concern associated with nuclear power is the production of radioactive waste, including uranium mill tailings, spent reactor fuel, and other radioactive materials. These substances can remain hazardous and radioactive for thousands of years, posing risks to human health. Radioactive waste is classified as low-level and high-level waste. By volume, most waste from the nuclear power industry exhibits relatively low radioactivity. Uranium mill tailings contain radium, which decays to produce radon, a radioactive gas. Other types of low-level radioactive waste include tools, protective clothing, wiping cloths, and other disposable items that become contaminated with small amounts of radioactive dust or particles at nuclear fuel processing facilities and power plants. High-level radioactive waste consists of spent nuclear reactor fuel, which is no longer useful for electricity production. The spent reactor fuel is in solid form, consisting of small fuel pellets in long metal tubes called rods. Spent reactor fuel assemblies are initially stored in specially designed pools of water, where the water cools the fuel and acts as a radiation shield. Spent reactor fuel assemblies can also be stored in specially designed dry storage containers. When a nuclear reactor ceases operation, it must be decommissioned. This process involves safely removing the reactor and all equipment that has become radioactive from service and reducing radioactivity to a level that permits other uses of the property (Freedman et al., 2024)

2.3.2 Renewable Energy

Renewable energy utilizes sources that are perpetually replenished on a human timescale, including sunlight, wind, rain, tides, waves, and geothermal heat. These sources are environmentally benign and are frequently regarded as sustainable alternatives to conventional fossil fuels. Renewable energy generates lower, or zero greenhouse gas emissions compared to fossil fuels, thereby contributing to the reduction of air pollution, the mitigation of climate change, the enhancement of public health, and the alleviation of smog and acid rain. Furthermore, the renewable energy sector holds the potential to generate employment and stimulate economic growth, particularly in the manufacturing and installation of renewable energy technologies. However, certain renewable energy sources, such as solar and wind, are intermittent and reliant on weather conditions, necessitating the development of storage solutions or backup power sources (Mekuye et al., 2024).

1. **Solar Energy:** The energy source in question is predicted on nuclear fusion occurring at the sun's core. Various methodologies exist for the collection and conversion of this energy, encompassing advanced devices that directly convert sunlight into electrical energy using mirrors, boilers, or photovoltaic cells, as well as solar water heating via solar collectors and attic cooling through solar attic fans for residential applications. Broadly, there are two primary categories of radiation conversion technologies: photovoltaic, which involves direct conversion to electricity, and solar-thermal, which encompasses solar heating, cooling, drying, thermal power plants, and related applications. Solar thermal technologies find utility in diverse applications such as crop drying, residential heating, industrial process water heating, hospital operations, air conditioning, food and medication preservation, and power generation. For low- to medium-power applications in remote locations, photovoltaic (PV) power is suitable for communication stations, rural television and radio, street lighting, water pumping,

refrigeration, and powering security cameras, typically requiring power in the range of one to ten kW. In rural areas not connected to the national grid, PV power can also be employed to supply electricity (H. N. Amadi et al., n.d.).

Solar energy holds a crucial and evolving role within the energy sector, presenting numerous advantages and opportunities for sustainable energy production. As a clean and renewable energy source, it does not emit harmful substances during electricity generation. By harnessing sunlight through photovoltaic (PV) panels or solar thermal systems, solar power contributes to the reduction of greenhouse gas emissions and the mitigation of climate change. It offers nations the opportunity to diversify their energy sources and reduce their reliance on imported fuels. By utilizing the abundant and freely available sunlight, regions can achieve enhanced energy independence and strengthen their energy security (Mekuye et al., 2024). While solar energy possesses considerable potential, it is not without its limitations. The distribution of solar energy is not uniform across the globe, rendering certain regions more favorable for solar energy investment than others. Furthermore, even in areas with high solar potential, solar energy can only be harnessed during periods of sunlight. Consequently, energy generation is minimal or nonexistent during nighttime or overcast conditions. Unlike coal, oil, or even biomass, sunlight cannot be stored and utilized on demand, presenting a significant challenge in addressing the issue of intermittent power supply (Freedman et al., 2024).

2. **Wind Energy:** Wind energy is a sustainable and renewable energy power source that minimizes emissions during electricity generation. However, the effectiveness of wind energy relies on the wind resources available at the location. Wind power plants are facilities that produce electricity using wind turbines. These plants convert the kinetic energy of the wind into electrical energy. A wind turbine transfers the motion

generated by the wind through rotors to a generator that rotates, thereby generating electricity (Khamroyevna, 2024). Winds are generated by variations in atmospheric pressure around the world. These pressure differences are primarily caused by difference in temperature resulting from uneven solar heating across the Earth. Consequently, wind power is an indirect form of solar energy. Like solar energy, certain areas of the Earth's surface have higher wind speeds, which enhances their ability to harness wind energy (Freedman et al., 2024). Wind energy production relies on the wind speed to rotate wind turbines; a minimum wind speed of 12–14 km/h is necessary to start turning and generate electricity, while a wind speed of 50–60 km/h is needed to produce electricity at full capacity. If the wind speed exceeds 90 km/h, the turbines halt to prevent damage (Mekuye et al., 2024).

3. **Hydropower:** Hydropower, also referred to as hydroelectric power, exploits the natural flow of water in rivers and streams to produce mechanical energy, which is then converted into electricity through turbines. In recent years, hydropower has become the foremost source of electricity generation. Typically, hydropower plants are located within dams that obstruct rivers, thereby creating the maximum possible hydraulic head (Mekuye et al., 2024). In the process of hydraulic energy production, water is primarily channeled through rivers or artificial reservoirs, where its potential energy is transformed into electrical energy. As water descends from a height, it converts potential energy into kinetic energy. The pressure exerted by the descending water rotates the rotors, which in turn generate electricity through a generator. Water flows through turbines, converting the water's motion into rotating mechanical energy. The rotating components of the turbine drive the generator, resulting in the production of electricity. Water resources are inherently renewable and inexhaustible, and the

generation of hydropower results in minimal waste and pollution (Khamroyevna, 2024).

4. **Geothermal Energy:** Geothermal energy is a type of renewable thermal energy found within the Earth's crust, originating from the radioactive decay of materials and plants. High pressure and temperature within the Earth's interior cause the rock to behave plastically, allowing the melted and solid mantle to move upward since it is lighter than the surrounding rock (Mekuye et al., 2024). A geothermal system requires heat, permeability, and water. To develop electricity from geothermal resources, wells are drilled in a location with high geothermal potential. This is typically a region containing naturally superheated groundwater. Groundwater percolates down through cracks in the subsurface rocks until it reaches rocks heated by underlying magma, and the heat converts the water to steam. Many areas with strong seismic activity, including earthquakes and volcanoes, also possess high geothermal potential (Freedman et al., 2024).
5. **Biomass:** Biomass energy is derived from living organisms and is either burned to produce heat or converted into electricity. It can be generated both artificially and naturally, stored in non-fossil organic materials like straw, wood, forestry waste, vegetable oils, agricultural products, and industrial waste. This energy originates from the sun, as plants absorb sunlight through photosynthesis, converting carbon dioxide and water into nutrients (carbohydrates). There are four types of biomass: wood and agricultural products, solid waste, landfill gas and biogas, and alcohol fuels such as ethanol or biodiesel. The energy from these sources is transformed into usable energy through direct (heat) and indirect (biofuel) methods (Mekuye et al., 2024). Various methods can be used to convert biomass into electrical energy. The most common technique is the direct combustion of biomass, such as wood or agricultural waste.

Other alternatives include anaerobic digestion, pyrolysis, and gasification. Gasification involves heating biomass with less oxygen than needed for complete combustion, resulting in a synthesis gas with usable energy content. Pyrolysis, on the other hand, quickly heats biomass in the absence of oxygen to produce bio-oil. Anaerobic digestion creates renewable natural gas by breaking down organic matter with bacteria in the absence of oxygen (Amadi et al., n.d.). Biomass can be transformed into more convenient energy carriers, such as liquid fuels (biodiesel, bioethanol, bio-oil), solid fuels (wood chips, firewood, charcoal, briquettes, pellets), gaseous fuels (hydrogen, synthesis gas, biogas), or heat directly from the production process. The combustion of biomass is considered carbon-neutral because the carbon dioxide released has already been absorbed by plants from the atmosphere. Biomass resources include wood waste from industry and forestry, agricultural residues, paper and food industry residues, animal manure, dedicated energy crops, sewage sludge, municipal green waste, starch crops like wheat and corn, sugar crops such as beet, sugarcane, and sorghum, oil crops like oilseed rape, soy, sunflower, palm oil, and jatropha, as well as grasses like Miscanthus. (Igwebuike et al., 2024a).

2.4 BIOFUELS

Biofuels encompass solid, liquid, and gaseous fuels derived from diverse feedstocks, including animal fats, agricultural waste (biomass), and waste oils. These fuels are characterized by their biodegradability, non-toxicity, and carbon neutrality, resulting in reduced emissions of carbon and greenhouse gases, as well as lower levels of carbon monoxide, nitrogen and sulfur oxides, unburnt hydrocarbons, and particulate matter when compared to fossil and conventional fuels (Malik et al., 2024). Biofuel is considered a secure energy source, serving as an alternative to finite fossil fuels, and is also environmentally beneficial since biomass is classified as carbon-neutral or greenhouse gas neutral (Chavan et al., 2024a). Biofuels offer advantages over conventional fuels and other renewable energy sources by reducing reliance on oil imports and emitting minimal or no pollutants that contribute to environmental pollution, health risks, and global warming. They complement traditional fossil fuels, derived from organic materials converted into fuel. When considering the overall costs and benefits, biofuels are more cost-effective, renewable, and abundant compared to fossil fuels. Globally, a sustainable biofuel market should focus on improving efficiency, optimizing production processes, and enhancing blending properties (D. Biofuels et al., 2024).

Biofuels are generally divided into three main categories: liquid, gaseous, and solid biofuels, based on their physical state at room temperature (B. Biofuels & El-Araby, 2024). Liquid biofuels have high energy density and are alternatives to conventional fuels used in aviation where petroleum-derived liquid fuels play a key role, whereas gaseous biofuels (i.e., biomethane and biohydrogen) offer greater benefits for public transportation and industrial combustion. Solid biofuels derived from waste biomass require low energy consumption for their production and have, by nature, a high calorific value in comparison with nonrenewable solid energy sources (i.e., firewood, charcoal, and lignite) that are commonly utilized to meet daily human needs (Quevedo-Amador et al., 2024a).

Depending on the processing before utilization, biofuels can be classified into primary and secondary biofuels.

1. **Primary Biofuels:** Primary biofuels, derived from wood, plants, and animals, are employed directly for cooking or heating without requiring pretreatment (Quevedo-Amador et al., 2024a). They are predominantly used for cooking, heating, agricultural activities, and electricity generation in both small and large-scale industrial contexts.

Known also as traditional biomass, primary biofuels have limited applications and do not necessitate processing resource expenditures (Igwebuike et al., 2024b).

2. **Secondary Biofuels:** Secondary biofuels are derived from the processing of biomass through thermochemical methods, such as transesterification, biological processes like fermentation, or the use of catalysts (Quevedo-Amador et al., 2024a). These biofuels, originating from primary biomass, can exist in solids (e.g., charcoal), liquids (e.g., bio-oil, ethanol, biodiesel), or gaseous forms (e.g., hydrogen, biogas, synthesis gas). They are applicable in a broader spectrum of uses, including high-temperature industrial processes and transportation, serving as alternatives to fossil fuels (Igwebuike et al., 2024b).

   Secondary biofuels can be categorized further into three main generations based on the feedstock used, as well as a fourth generation that is beginning to utilize biogenetic engineering. The first generation of biofuel production utilizes food crops such as corn and sugarcane. The second generation employs non-food plants and waste materials, including agricultural residues and wood chips. The third generation focuses on algae, which can rapidly produce substantial quantities of biofuels. A nascent fourth generation is emerging, characterized by the application of genetic engineering to enhance biofuel production. This fourth generation involves the modification of plants and microorganisms to increase the efficiency of biofuel production and to capture carbon dioxide from the atmosphere, thereby enhancing their environmental sustainability.(B. Biofuels & El-Araby, 2024).

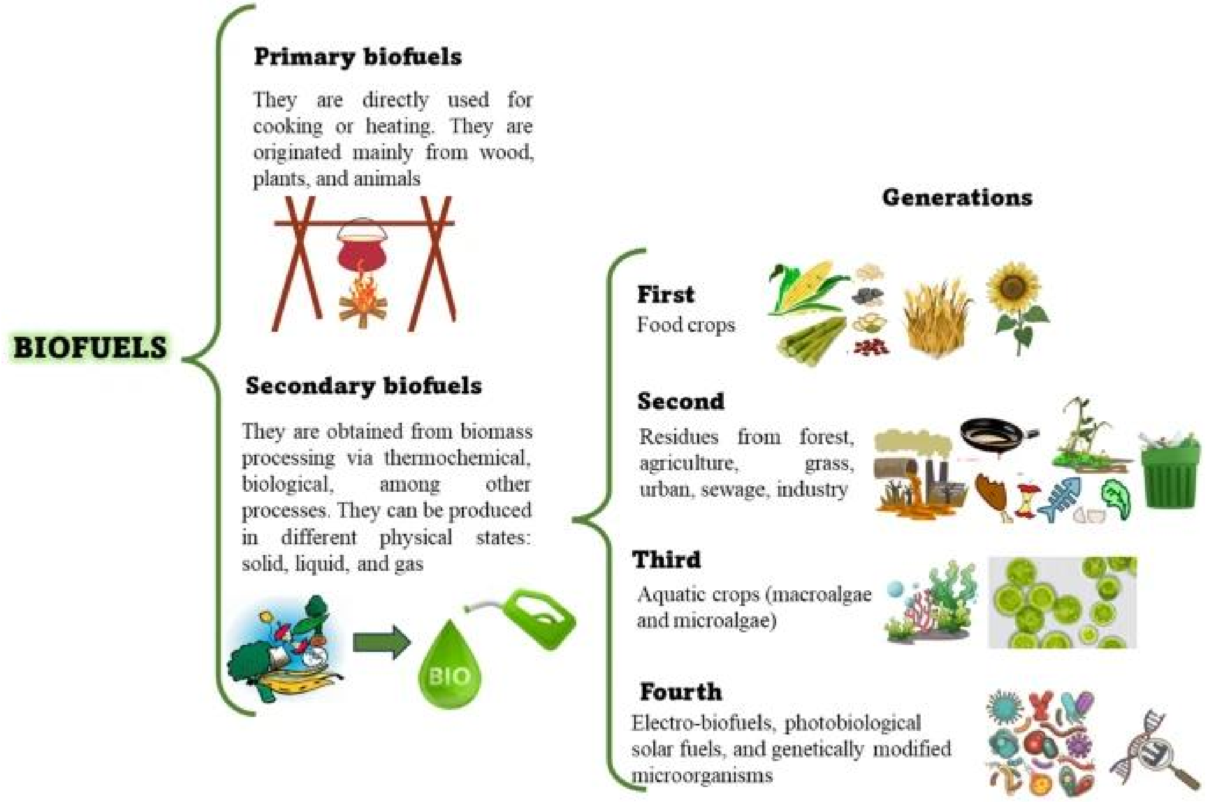

Figure 2. 1: Classification of biofuels and their generations

2.4.1 Generations Of Biofuels

1. **First generation:** First-generation biofuels are obtained from edible raw materials such as high lipid-containing seeds [e.g., soybean] (Quevedo-Amador et al., 2024a). These biofuels are generated through established methods such as cold pressing, extraction, transesterification, hydrolysis, saccharification, fermentation, and chemical synthesis, and have been optimized for commercial production. They are primarily derived from sources like starch, sugar, grains, animal fats, and vegetable oils (D. Biofuels et al., 2024). However, their reliance on consumable crops, which heightens competition for food supplies, presents inherent sustainability issues (Ali Ijaz Malik et al., 2024). First-generation biofuels help improve energy security and reduce carbon emissions, they compete with food supply, which raises food prices and affects land

use and biodiversity. Despite these concerns, first-generation biofuels like biodiesel, bioethanol, and biogas are already being produced commercially and are used in existing fuel systems (Igwebuike et al., 2024a).

2. **Second-generation:** The discussion surrounding first-generation raw materials for food security has prompted a move towards second-generation lignocellulosic raw materials, which are obtained from nonfood biomass of plants or animals (B. Biofuels & El-Araby, 2024). This generation of biofuels are derived from lignocellulosic materials like corn straw, wheat straw, sugarcane bagasse, sugar beet pulp, cassava peels, and switchgrass, including both softwood and hardwood. These biofuels utilize biomass that are not suitable for food consumption (non-edible biomass). They include plants primarily grown for energy production, such as bioenergy crops on marginal lands (lands unsuitable for food production), or non-edible parts of crops and forest trees. Lignocellulose, which forms the cell walls of plant biomass, consists of three main components: cellulose (30–50%), hemicellulose (10–40%), and lignin (5–20%) (Igwebuike et al., 2024b). The conversion process of second-generation feedstock can be achieved through two primary methods: thermochemical and biological. Thermochemical decomposition processes include gasification, bio carbonization, liquefaction, and pyrolysis. Biological digestion mainly involves microbial fermentation. Typically, the biological digestion process is very common and yields a small number of different products with high efficiency in the presence of certain biological catalysts. The thermochemical conversion process generates multiple and complex products within short reaction times and utilizes inorganic catalysts to enhance product quality (D. Biofuels et al., 2024). This generation process separates plant components, lignin and cellulose, which can then be converted into ethanol. Second generation biofuels, derived mainly from lignocellulosic

biomasses of non-food energy-producing plants and agro-waste, address most of the constraints associated with the development of first-generation biofuels (Chavan et al., 2024). Due to its abundance and easy availability, lignocellulosic biomass makes second-generation biofuels a highly attractive alternative. These feedstock sources contribute to making biofuel production more economical, efficient, sustainable, and environmentally friendly. However, it is widely recognized that second-generation biofuels may not be entirely profitable, as the equipment and technologies required to produce commercial products that meet established quality standards are generally expensive (Quevedo-Amador et al., 2024a). Second-generation biofuels are essential for advancing the bioenergy sector, offering a more sustainable alternative to traditional fossil fuels and addressing some of the drawbacks of first-generation biofuels. Continuous research and innovation in this field aim to enhance the feasibility and environmental advantages of second-generation biofuels (Technology & 2024, 2024). The primary resources for second-generation biofuel production include biomass-to-liquids (BTLs), biobutanol, and bioethanol derived from lignocellulosic biomass (Malik et al., 2024a).

3. **Third generation:** Third generation biofuel, often referred to as 'algae fuel,' is derived from algae. Algae produce a variety of biofuels, including biodiesel, propanol, butanol, ethanol, and gasoline, with an output nearly ten times higher than that of second-generation biofuel (Chavan et al., 2024b). Compared to other energy crops, algae is a highly efficient photosynthetic feedstock, converting solar energy into chemical energy and storing it as oils, carbohydrates, and proteins (Malik et al., 2024). Algae stands out among other energy sources due to its high lipid and nutrient content, making it an appealing option for biofuel production. Additionally, algae excel in capturing greenhouse gases (CO2), adapts easily, grows rapidly in various water

bodies (such as wastewater, freshwater, and seawater), and has high photosynthetic efficiency (Quevedo-Amador et al., 2024a). Algae can generate higher yields with fewer input resources compared to other biomass, which is why it is classified separately from second-generation biofuels. In terms of fuel production potential, both in quantity and diversity, no feedstock can match algae. Algae have two key attributes regarding the diversity of fuel it can produce: (i) it produces oil that can be easily refined into diesel or certain gasoline components, and (ii) it can be genetically modified to produce fuels like ethanol, butanol, diesel, and gasoline (Igwebuike et al., 2024a). Algal biofuels could be better alternatives to earlier generations because they grow faster and don't require extensive land or resources. Algae perform photosynthesis more quickly than the land plants used in first and second-generation biofuels. Their significance lies in not competing with food chains while offering various end products like bioethanol, biogas, and biodiesel (B. Biofuels & El-Araby, 2024).

4. **Fourth generation:** biofuels represent an advanced category of renewable fuels, synthesized through the utilization of genetically engineered algae and microorganisms. These biofuels, often referred to as photosynthetic or algal biofuels, are derived from organisms that harness sunlight to generate energy. A distinctive feature of these biofuels is their dual function: they are engineered not only to produce fuel but also to capture and isolate substantial quantities of carbon dioxide, thereby rendering them carbon-negative (D. Biofuels et al., 2024). These organisms function as carbon capture systems, storing carbon in various components such as leaves and branches, which can subsequently serve as biofuel feedstock. This field is in a state of development, with ongoing research dedicated to optimizing the conversion of renewable energy into electricity. The production of biofuels in this category involves

the use of modified plants and microbes, with variations in feedstock quality and operational conditions across different cases. Consequently, the technologies and resultant biofuel products differ based on the specific processes employed (Chavan et al., 2024a). These modified photosynthetic feedstocks are renewable, cost-effective, and readily available. It is important to acknowledge that, despite the advancements achieved in this generation of biofuels, they remain in the developmental phase and have not yet reached large-scale commercialization or industrial implementation.(Quevedo-Amador et al., 2024a).

Biofuels produced through fermentation primarily include biogas, bioethanol, biobutanol, and biodiesel. Liquid biofuels possess a higher energy density, rendering them more advantageous for transportation and storage compared to gaseous fuels such as biogas. Bioethanol, characterized by its low boiling point and high-octane number, can be blended with gasoline to reduce CO2 emissions. Biodiesel, due to its chemical similarity to conventional diesel, can be mixed with fossil diesel. Biobutanol is particularly promising owing to its superior properties relative to bioethanol, including higher energy density and generally lower water content attributable to increased hydrophobicity. Furthermore, biobutanol is less volatile and less corrosive, facilitating safer and more convenient usage and storage. Notably, biobutanol has the potential to completely replace gasoline, whereas ethanol is limited to use as an additive.(Technology & 2024, 2024).NMA

2.4.1 Biodiesel

Biodiesel is composed of fatty acid alkyl esters (FAAEs). These fatty acids are derived from the triglycerides (TAGs) present in vegetable and animal fats and oils, while the alkyl group in the ester is typically a methyl or ethyl group. Consequently, biodiesel primarily consists of fatty acid methyl esters (FAMEs), fatty acid ethyl esters (FAEEs), or a combination of both

(Spanou et al., 2024). Biodiesel is generally obtained using four conventional methods: direct blending or dilution, microemulsion, thermal cracking/pyrolysis, and transesterification (Quevedo-Amador et al., 2024b). Transesterification is a widely used method for converting various types of waste into biodiesel. It requires pretreatment to remove impurities from all waste sources and is effective for lipid-rich materials like agricultural waste, waste cooking oil, and algal lipids. This method ensures efficient conversion to biodiesel by converting triglycerides (TAGs) into fatty acid methyl esters (FAME) and glycerol through a reaction with an alcohol (typically methanol) in the presence of a catalyst. The catalyst can be a base (NaOH or KOH), acidic (H_2SO_4), or enzymatic (Lipases). This reaction produces diglycerides and methyl esters. (Ali Ijaz Malik et al., 2024). The elevated viscosity and hygroscopic properties of glycerol pose considerable challenges to the quality of biodiesel. These stringent limitations are crucial, as even minimal quantities of glycerol can adversely affect engine performance and durability. An excess of glycerol may lead to the formation of gum-like deposits around vital engine components, such as injector tips and valve heads, which can impede fuel flow, reduce combustion efficiency, and potentially result in engine knocking or misfiring. Adhering to the established guidelines for glycerol content is crucial to prevent engine malfunctions and ensure optimal performance. Achieving compliance with these stringent standards necessitates extensive purification of biodiesel. Various purification techniques, including wet washing, dry washing, distillation, membrane separation, adsorption, and solvent-assisted crystallization, are employed to eliminate impurities and attain the requisite purity levels (Wan Osman et al., 2024). Biodiesel has attracted significant attention due to its compatibility with existing combustion engines, requiring no substantial modifications. It offers notable advantages, including biodegradability, low toxicity resulting from reduced sulfur and aromatic content, and a high oxygen concentration, which enhances combustion efficiency compared to petroleum-based diesel. Moreover, biodiesel possesses a higher cetane number, an additional indicator of diesel quality. These characteristics of biodiesel improve engine lubrication and extend its shelf life. Given its similar physicochemical properties to petroleum-derived diesel, biodiesel can be either blended with it or used directly (Spanou et al., 2024). Biodiesel presents numerous advantages for diesel engines, including a high flash point, elevated cetane number, and increased oxygen content. Additionally, it is devoid of aromatics and contributes to the reduction of greenhouse gas emissions, positioning it as a formidable competitor to conventional fuels (Basumatary et al., 2024).

2.4.2 Bioethanol

Bioethanol is a type of alcohol (ethanol) produced through the microbial fermentation of plant or algal carbohydrates, such as lignocellulosic biomass, wheat, sugarcane, maize, and others. This natural process involves breaking down larger organic molecules into simpler ones (Abdul Kareem Joyia et al., 2024). Bioethanol production typically involves hydrolyzing various lignocellulosic biomasses to extract sugars, which are then fermented by different microorganisms. The yeast Saccharomyces cerevisiae is commonly used for this process at an optimal temperature range of 30–35 °C. However, the raw material used can affect the process, so combining pretreatment methods can lead to better bioethanol yields (Quevedo-Amador et al., 2024a). This biofuel can be used directly in vehicles and functions similarly to traditional fuels. Additionally, due to its high-octane rating, bioethanol allows for increased engine compression ratios, which enhances engine performance and efficiency. Compared to gasoline, which lacks oxygen, bioethanol is an environmentally friendly oxygenated fuel, containing 34.7% oxygen. This results in approximately 15% greater combustion efficiency for bioethanol than gasoline, leading to lower emissions of particulate matter and nitrogen oxide (Chavan et al., 2024a). Bioethanol is a promising substitute for fossil-based transportation fuels due to its broader flammability limits, higher octane rating, greater heat of vaporization, and faster flame speeds. These characteristics allow for shorter burn times, higher compression ratios, and leaner burn engines, providing a theoretical efficiency advantage over gasoline in internal combustion engines. Mixing ethanol with petrol enhances the latter's performance and improves fuel combustion in vehicles, reducing emissions of unburned hydrocarbons, carbon monoxide, and carcinogens (Igwebuike et al., 2024a).

2.4.3 Biogas

Biogas is a renewable energy source produced from biomass, such as agricultural waste, food scraps, animal manure, and even sewage. The process used to produce biogas is called anaerobic digestion, where microorganisms break down organic materials in the absence of oxygen to release a mixture of gases, mainly methane (CH_4) and carbon dioxide (CO_2). This gas can be used for cooking, heating, lighting, and even electricity generation (Jameel et al., 2024). The most valuable component of biogas is methane. The higher the methane content, the better the quality and economic value of the biogas. It is colorless, tasteless, and has a distinct rotten egg smell due to trace gases like H_2S. As a greenhouse gas, biogas is 25 times more potent than CO_2, making proper usage important for the environment. It burns with a blue flame at around 800°C and has a high ignition speed when mixed with air in a 1–20 ratio. These properties make biogas efficient for energy use while helping reduce environmental pollution (Jameel et al., 2024).

Anaerobic digestion is a crucial process for sustainable waste management and renewable energy production. The generation of biogas through anaerobic digestion involves four key steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In the hydrolysis phase, complex organic materials such as carbohydrates, proteins, and lipids are broken down into simpler compounds by hydrolytic bacteria, producing soluble sugars, amino acids, and fatty acids. This is followed by acidogenesis, where acidogenic bacteria ferment these simpler compounds into Volatile Fatty Acids (VFAs), hydrogen, and carbon dioxide. Next, during acetogenesis, the VFAs are converted into acetic acid and additional hydrogen and carbon dioxide by acetogenic bacteria, with acetic acid serving as a crucial substrate for the next step. Finally, methanogenesis occurs, where methanogenic archaea convert acetic acid and hydrogen into methane and carbon dioxide, making this step essential for biogas production. Each of these steps is interdependent, and the balance of microbial communities in AD is fundamental for the efficient breakdown of organic matter and stable biogas production (Mohammadianroshanfekr et al., 2024).

To ensure efficient degradation, it's important to consider the conditions for anaerobic digestion (AD) because the biological processes are sensitive to certain parameters like operating temperature, pH, and ammonia levels in the digester. There are four types of digestion temperatures used for anaerobic digestion: psychrophilic (operating within the temperature range of 4 to 25°C), mesophilic (operating within the temperature range of 30 to 40°C), thermophilic (operating within the temperature range of 50 to 60°C), and extremophilic (operating within the temperature range of above 70°C). Most digesters operate within the mesophilic and thermophilic ranges, depending on the feedstock (Tjutju et al., 2024). The phases of anaerobic digestion, namely hydrolysis, acidogenesis, acetogenesis, and methanogenesis, are interconnected, making their coordination crucial for the overall efficiency of the digestion process. Each phase contributes specific biochemical changes that aid in the conversion of organic matter into biogas (Ngabala & Emmanuel, 2024a).

The production of biogas prevents methane emissions into the atmosphere and contributes to a net reduction in greenhouse gas emissions. The suitability of biomass as a substrate for biogas production largely depends on its nutritional composition. These compositions affect the biogas yield, methane content, biodegradability, and degradation kinetics of the biomass. The key nutritional components of interest in substrates include carbohydrates, proteins, and fats. The digestate retains most of the nutrients that enter the process, making it a valuable biological fertilizer (Draghici et al., n.d.). Biogas production significantly advances sustainable energy by converting organic waste into valuable resources like biogas, biosolids, and liquid fertilizer, thus promoting waste reduction and energy recovery. Additionally, biogas plays a crucial role in sustainable energy generation due to its renewable nature, diverse applications, and positive environmental impact. The process of producing biogas and converting it into renewable methane provides numerous opportunities for various industries to align with their sustainability goals by utilizing waste streams as raw materials, leading to a significant reduction in their overall environmental footprint (Phillip et al., 2024).

2.4.3.1 Phases Of Anaerobic Digestion

Anaerobic digestion (AD) is a biological process employed for the treatment of organic waste and the generation of biogas. This process unfolds in four interconnected stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Each stage is characterized by specific microbial activities that decompose complex materials into simpler molecules, ultimately resulting in the production of methane (CH_4) and carbon dioxide (CO_2).

1. **Hydrolysis:** It constitutes the initial phase, wherein complex organic substances such as carbohydrates, fats, and proteins are decomposed into their soluble monomers, including sugars, amino acids, and fatty acids. This step is essential as it prepares the waste materials for subsequent microbial conversion (Ngabala & Emmanuel, 2024, p. 3). The hydrolysis of cellulose is represented by the reaction:

$$[C6H10O5]n + nH2O \rightarrow nC6H12O6 + nH2 \qquad 2.1$$

2. **Acidogenesis:** During the acidogenesis phase, the previously generated soluble organic molecules are converted into volatile fatty acids (VFAs), alcohols, CO_2, hydrogen, and other intermediates by fermentation. These compounds function as

precursors for methane production. Additionally, acidogenesis contributes to the reduction of organic complexity and prepares the system for subsequent gas formation (Phillip et al., 2024, p. 768). The primary product at this stage is CH3COOH, a significant organic acid that serves as a precursor for microorganisms that generate CH_4^- (Ngabala & Emmanuel, 2024b). The equations below illustrate the chemical reactions that take place during the acidogenesis phase.

$$C6H12O6 \rightarrow 2CH3CH2OH + 2CO2 \tag{2.2}$$

$$C6H12O6 \rightarrow 3CH3COOH + 2H2 \leftrightarrow 2CH3CH2COOH + 2H2O \tag{2.3}$$

3. **Acetogenesis:** During this stage, acetogenic bacteria convert fermentation products such as alcohols, aldehydes, and volatile fatty acids (VFAs) into acetic acid, hydrogen, and CO_2. The acetate produced becomes the main substrate for methanogenic microorganisms. Acetogenesis is essential for maintaining system balance and enhancing gas production efficiency by eliminating excess acids and supplying acetate (Phillip et al., 2024). Homoacetogens, bacteria that utilize hydrogen, employ the acetyl-CoA pathway primarily for the reductive synthesis of acetyl-CoA from CO2. This pathway also serves as their terminal electron-accepting, energy-conserving step and is used for producing cell carbon from CO_2 (Ngabala & Emmanuel, 2024b). The equations demonstrate the chemical reactions occurring in the acetogenesis phase.

$$CH3CH2COO + 3H2O + 2e - \rightleftharpoons CH3COO - + H + + HCO3 - + 3H2 \tag{2.4}$$

$$C6H12O6 + 2H2O \rightleftharpoons 2CH3COOH + 2CO2 + 4H2 \tag{2.5}$$

$$CH3CH2OH + 2H2O \rightleftharpoons CH3COO + 3H2 + H + \tag{2.6}$$

$$2HCO3 - + 4H2 + H + + e - \rightleftharpoons CH3COO + 4H2O \tag{2.7}$$

4. **Methanogenesis:** In the final stage of degradation, known as methanogenesis, two groups of methanogenic bacteria actively produce methane from acetate or from hydrogen and carbon dioxide. These bacteria exhibit strict anaerobic characteristics, requiring a lower redox potential for growth compared to most other anaerobic bacteria, highlighting complex and selective mechanisms in the biological processes involved in biogas production (Phillip et al., 2024). Methanogens are organisms that thrive exclusively in anaerobic environments, meaning they require the absence of oxygen to survive. Consequently, they are extremely sensitive to even minimal levels of oxygen, which can be detrimental to their existence. The equations demonstrate the chemical reactions occurring in the acetogenesis phase (Ngabala & Emmanuel, 2024b). The equations demonstrate the chemical reactions occurring in the acetogenesis phase.

$$CH3COOH \rightarrow CH4 + CO2 \qquad 2.8$$

$$CO2 + 4H2 \rightarrow CH4 + 2H2\ O \qquad 2.9$$

$$2CH3CH2OH + CO2 \rightarrow CH4 + 2CH3COOH \qquad 2.10$$

The four stages are intricately interconnected and must operate in harmony under optimal conditions, such as appropriate temperature, pH balance, and carbon-to-nitrogen ratio, to ensure successful and efficient biogas production (Phillip et al., 2024).

2.4.4.2 Feedstock For Biogas Production

1. Kitchen Waste

Kitchen waste, comprising various organic materials such as food scraps and leftovers, is acknowledged as a valuable resource for biogas production. This common household byproduct is abundant in organic compounds, notably volatile solids (VS), which are essential for anaerobic digestion. Research indicates that kitchen waste typically contains 85-96% volatile solids, highlighting its substantial potential as an effective substrate for methane generation through anaerobic digestion. Rigorous analysis and classification processes have identified numerous categories of kitchen waste. These categories encompass a diverse range of sources, including hot pot (HP), fast food (FF), Hebei cuisine (HC), university canteen (UC), households, packaging materials, and other forms of mixed kitchen waste, each presenting unique characteristics and implications for waste management practices (Phillip et al., 2024).

2. Municipal solid waste

Municipal solid organic waste comprises biodegradable materials, including food waste, kitchen scraps, garden and park trimmings, as well as waste from restaurants and catering services. These materials are particularly amenable to anaerobic digestion, facilitating their conversion into biogas, thereby enabling energy recovery from waste. However, the heterogeneous and inconsistent composition of this waste necessitates proper sorting prior to effective processing (Ćurčić et al., 2025). Municipal solid waste (MSW) contains a substantial amount of biodegradable organic material that can be utilized to generate biogas through anaerobic digestion. Often, MSW is co-digested with other materials, which enhances the degradation process and subsequently increases biogas production. Numerous studies have investigated the methane yield from the anaerobic decomposition of the organic fraction of municipal waste (OFMSW). For instance, research indicates that the sorted organic fraction of MSW can yield approximately 300 to 400 normal cubic meters of methane per ton of volatile solids (VS), with an approximate 80% reduction in VS (Ngabala & Emmanuel, 2024).

3. Animal manure

Animal manure represents the predominant source of organic waste in agriculture and is rich in plant nutrients, which is why it is commonly utilized by farmers to enhance soil quality. Additionally, it serves as a substrate for biogas production, with the residual material, known as digestate, remaining useful for soil conditioning. The anaerobic decomposition of manure increases the availability of nitrogen for plants, thereby enhancing its efficacy as a soil conditioner. Despite its agricultural benefits, improper management of animal manure can pose environmental risks, including malodors, disease transmission, and the emission of carbon dioxide, a contributor to global warming. Manure can be processed in both liquid and solid forms for biogas production, with research indicating that liquid manure yields a higher biogas output. Notably, manure is distinguished by its rich nutrient content, including trace metals, vitamins, and other essential chemicals that support microbial activity, making it particularly suitable for anaerobic digestion (Ngabala & Emmanuel, 2024). However, relying solely on animal manure for anaerobic digestion does not produce as much biogas as other methods. Furthermore, the high nitrogen content of manure makes it an effective supplement for feedstocks with lower nitrogen levels. As a readily available and consistent resource, manure holds significant potential in co-digestion processes. Economically, co-digesting manure is generally more advantageous than utilizing it in mono-digestion (Kaitale, 2024).

Animal manure is a significant source of nitrogen, as evidenced by the nitrogen content in fresh goat manure (1.01%), chicken manure (1.03%), cattle manure (0.35%), and pig manure (0.24%). Notably, pig manure exhibits a low carbon-to-nitrogen (C/N) ratio, approximately 6 to 8, which is suboptimal for anaerobic digestion processes. To achieve a balanced C/N ratio, facilitate bacterial proliferation, and mitigate issues such as ammonia accumulation and acidification, it is advisable to combine animal manure with crop residues during biogas production. Animal manure is particularly suitable for anaerobic digestion due to several factors: its high-water content aids in diluting concentrated by-products and simplifies the pumping process; its substantial buffering capacity is essential for preventing abrupt pH changes; and it provides a diverse array of nutrients necessary for microbial growth (Draghici et al., n.d.).

CHAPTER THREE

MATERIALS AND METHODS

3.1. MATERIALS

The primary feedstocks used in this study for biogas production through co-digestion were fresh cattle rumen, cassava peels, yam peels, and potato peels. These materials were selected due to their high organic content, local availability, and potential for synergistic effects in anaerobic co-digestion, which can enhance biogas yield and process stability. The feedstocks were sourced from various locations in Benin City, Edo State, Nigeria, ensuring the use of locally abundant organic waste to promote sustainable waste management and renewable energy production. For the apparatus, Table 3.1 below shows the list of apparatus used during

Table 3. 1: Apparatus used

Apparatus	**Function/uses**
Local hand grinder	Reducing particle size during pretreatment of feed
Buchner flask	For digesting
Rubber seal	For sealing the Buchner flask to prevent gas from

	escaping from the flask during digestion
Porcelain crucibles	It was used as a containment when heating feedstock to a high temperature
Mortal and pestle	For determining pH of solution
Stirrer	For agitation of the slurry in the bio-digestate
Desiccator	It is used in cooling the crucibles from the furnace
Gas pipe or Hose	For the transfer of gas produced
Bio-digester	For digesting
Beaker	For transfer and supply of measured volumes of liquids
Measuring Cylinder	For measuring volume of gas produced
Measuring Cylinder	Measurement of specific volumes of solution
Analytical weighing balance	For determining mass in grams

Table 3. 2: Equipment used

Equipment	Make	Function/uses
Oven heater		For reducing moisture in feed stock
Gas analyser		For analysing the methane yield in biogas
EDXRF spectrometer		For elemental analysis during characterization
Muffle furnace		For carrying out ash content and volatile matter content
Pressure guage		To determine the pressure build up in the digeste

3.1.1 Materials Collection

The cow dung was obtained fresh from Abattoir Oluku, Ovia northeast local government area, Benin city, Edo State. The rumen contents were collected immediately after slaughter to ensure minimal degradation and contamination. The material was gathered in clean, airtight polyethylene bags to prevent exposure to air, which could initiate aerobic decomposition and affect the anaerobic digestion process. During the collection process, direct coordination with slaughterhouse personnel to ensure the rumen was free from non-organic contaminants such as plastics or metals.

Cassava peels were sourced from a waste dump site at cassava processing units located in the Ogba community, Oredo Local Government Area, Benin city, Edo State. The peels were collected from freshly discarded waste to ensure they retained sufficient organic matter for biogas production. Care was taken to select peels free from soil, sand, or other inorganic impurities that could interfere with the digestion process. The cassava peels were kept in clean polyethylene bags to avoid unwanted substances during transit.

Yam peels and potato peels were collected from waste bins in Ekosodin, Ugbowo community, located in Ovia North Local Government Area, Edo State. These peels were sourced from household and small-scale street food vendors in the community. To ensure quality, only fresh peels without signs of rot or fungal contamination were selected. The peels were carefully sorted to remove any non-biodegradable materials, such as plastic wrappers or metal debris, and were stored in clean polyethylene bags to prevent moisture loss and microbial activity prior to processing.

3.2. FEEDSTOCK PRE-TREATMENT

The pre-treatment of feedstocks is a critical step in anaerobic digestion to enhance the accessibility of organic matter to microbial degradation, thereby improving biogas yield and process efficiency. The feedstocks cassava peels, yam peels, potato peels, and cattle rumen were subjected to specific pre-treatment processes to reduce particle size, remove impurities, and optimize their biochemical properties for co-digestion. The pre-treatment methods were designed to increase surface area, facilitate hydrolysis, and ensure uniformity in feedstock composition, which are essential for efficient biogas production.

3.2.1 Pre-Treatment of Cassava Peels

2 kg of fresh cassava peels, sourced from a waste dump site in the Ogba community, Edo State, was subjected to a multi-step pre-treatment process. The peels were first soaked in clean water for 2 hours. The soaking of cassava peels in clean water helps reduce the hydrocyanic acid (HCN) content by leaching cyanogenic compounds, with longer durations enhancing the yield of biogas (Agustin et al., 2024)."

After soaking, the peels were thoroughly washed to ensure cleanliness and eliminate any residual contaminants that could inhibit microbial activity during digestion. The cleaned peels were then dried in an oven heater at a temperature range of 100–130°C for 18 hours to reduce moisture content, which enhances grinding efficiency and prevents microbial spoilage during storage. The dried peels were crushed using a mortar and pestle to reduce particle size initially, followed by grinding with a manual hand grinding machine to achieve a finer consistency. Finally, the ground material was sieved through a 500-micron mesh to ensure a uniform particle size, which improves the surface area available for microbial degradation and enhances biogas yield

3.2.2. Pre-Treatment Of Yam Peels

A 2kg sample of yam peel were collected from waste bins in the Ekosodin, Ugbowo community. The peels were washed with clean water to remove dirt and organic residues, ensuring the material was free from contaminants that could affect the anaerobic digestion process. The washed peels were dried in an oven heater at 100 – 130°C for 18 hours to reduce moisture content, facilitating subsequent grinding and preventing microbial growth. The dried yam peels were then crushed using a mortar and pestle to break down the fibrous structure, followed by grinding with a manual hand grinding machine to achieve a finer particle size. The ground material was sieved through a 500-micron mesh to ensure uniformity in particle size, which is critical for optimizing the hydrolysis phase of anaerobic digestion and improving biogas production efficiency (Odejobi et al., 2016).

3.2.3. Pre-Treatment Of Potato Peels

A 2 kg sample of potato peels were sourced from waste bins in the Ekosodin, Ugbowo community. The peels were washed thoroughly with clean water to remove any adhering dirt or organic matter, ensuring the material was suitable for anaerobic digestion. The cleaned peels were dried in an oven heater at 100 – 130°C for 18 hours to reduce moisture content, which aids in grinding and preserves the material's organic content. The dried potato peels were crushed using a mortar and pestle to reduce particle size, followed by grinding with a manual hand grinding machine. The ground material was then sieved through a 500-micron mesh to achieve a uniform particle size, enhancing the accessibility of the substrate to anaerobic microorganisms The cattle rumen, obtained fresh from a slaughterhouse in Benin City, was used as collected without extensive pre-treatment to preserve its natural microbial population, which serves as an inoculum for anaerobic digestion. The cow dung was inspected to ensure the absence of non-organic contaminants (e.g., plastics or metals) and stored in a clean polyethylene bag at 4°C to ensure it is not contaminated. No additional grinding or drying was performed, as the rumen's high moisture content and inherent microbial activity are beneficial for co-digestion with the carbon-rich peels.

Plate 3. 1: Yam peels after processing

Plate 3. 2: Yam peels before processing

Plate 3. 3: Potato peel before processing

Plate 3. 4: Potato peel after processing

Plate 3. 5: Cassava peels before processing

Plate 3. 6: Cassava peels after processing

3.3. PROXIMATE ANALYSIS

3.3.1. MOISTURE CONTENT

The method used in carrying out this moisture content test was the hot air oven drying method which was adapted from the Association of Official Analytical Chemists (AOAC, 2010). Porcelain crucibles were washed and dried in an oven at 100°C for 40 minutes to ensure that there is no moisture in it to prevent errors. It is then cooled about 7g of substrate was placed into the weighed crucibles which were moisture free, and it is kept in the oven at about 109 °C for about 3 to 4 hrs. The sample was carefully removed from the oven and was cooled and weighed. It was kept back in the oven until the sample had the same weight.at different time interval giving enabling us to tell that the sample is moisture free. The moisture content is calculated based on the loss in weight of the sample and it is calculated by the formular below

$$\frac{\boldsymbol{W_1 - W_2}}{\boldsymbol{W_1}} \times \mathbf{100\%} \qquad \mathbf{3.1}$$

W_1=Weight of sample before drying

W_2 = weight of sample after drying

3.3.2. ASH CONTENT

The ash content was determined to quantify the inorganic residue in the feedstocks, which indicates the presence of non-combustible minerals that do not contribute to biogas production. A high ash content can reduce the organic matter available for digestion and may affect digester performance by accumulating as sludge (Okudoh et al., 2014). The following procedures were followed in determining the ash content of the substrates

i. Porcelain crucibles were washed and dried in an oven at 100°C for 40 minutes to ensure that there is no moisture in it.
ii. The weight of the dried Porcelain crucibles is measured and recorded as W_3
iii. About 3g sample of each dried feedstock (obtained after moisture content analysis) was placed in a pre-weighed porcelain crucible.
iv. The samples were incinerated in a muffle furnace at 700°C in the presence of air for about 4 hours to combust all organic matter, leaving only the inorganic ash.
v. The crucible was cooled in the desiccator, and after cooling, was weighed again and recorded
vi. The ash content was calculated by the formular below

$$\%\,\boldsymbol{ash\ content} = \frac{\boldsymbol{W_2}}{\boldsymbol{W_3}} \times \mathbf{100\%} \qquad \mathbf{3.2}$$

W_3=weight of dried feedstock.

W_2 = weight of feedstock after combustion in the furnace.

3.3.3. VOLATILE MATTER CONTENT

This is the material that is driven off when coal is heated to a high temperature in the absence of air under specified conditions. It consists of aliphatic carbon atoms (linked in open chains) or aromatic hydrocarbon. The volatile matter content was determined to assess the proportion of organic material in the feedstocks that can be converted into biogas during anaerobic digestion. Volatile organic matter test helps to indicate the organic content in the substrate that can be broken down by microorganisms to produce biogas (primarily methane and carbon dioxide). The following procedures were followed in determining the ash content of the substrates.

i. Porcelain crucibles were washed and dried in an oven at 100c for 40 minutes to ensure that there is no moisture in it.
ii. About 3g sample of dried feedstock (obtained after moisture content analysis) was measured with a digital weighing balance and placed in a pre-weighed dried porcelain crucible.
iii. The sample was heated in a muffle furnace at 950°C for 7 minutes, allowing volatile organic compounds to be released without combusting the fixed carbon.
iv. The crucible was cooled in the desiccator, and after cooling, was weighed again and recorded

The volatile matter content was calculated by the formular below

$$\frac{W_5 - W_6}{W_5} \times 100\% \qquad 3.3$$

Where:

W_5 = weight of dry feedstock

W_6 = weight of feed stock from the furnace.

3.3.4. FIXED CARBON CONTENT

The fixed carbon content is the carbon found in the material which is left after the volatile materials are driven off. This differs from the ultimate carbon content of coal because some carbon is lost in hydrocarbon with the volatile matter the fixed carbon was estimated according to the equation below.

$$\%\boldsymbol{FC} = \frac{\boldsymbol{Mass\ after\ carbonization}}{\boldsymbol{Mass\ before\ carbonization}} \times \mathbf{100}\% \qquad \mathbf{3.4}$$

Where:

FC is the Fixed Carbon.

3.4. ULTIMATE ANALYSIS

3.4.1. ELEMENTAL COMPOSITION

The elemental composition was carried out by using EDXRF (Energy Dispersive X-RAY Fluorescence) method. This analysis sends the samples which were already grinded to the x ray florescence analyser device. This test was important in determining the weight concentration of carbon, nitrogen and other elements present in the cow dung.

3.4.2 CARBON NITROGEN RATIO

The carbon nitrogen ratio for each feed stock was calculated by dividing the composition of carbon from elemental analysis by the composition of nitrogen from elemental analysis.

3.5. EXPERIMENTAL DESIGN

The experimental design was done using design expert software. The optimal mixture design was used for experiment. The Design of Experiment (DOEs) method provides an impressive tool for optimization of the processes and determining the optimal formula for a particular mixture. To evaluate the effect of anaerobic co-digestion on the yield of biogas as a response variable under 3 independent factors, the optimal mixture design was used. These factors represent the fraction of each feedstock the yam peel, cassava peels and potato peels in the mixture, which varies from zero to one without limitation in the design space.

Based on the experimental design from simplex lattice 12 runs of experimentation were to be carried out and the experiment was carried out with a fixed mass of cow dung which we used 50g of cow dung in each run and it was dissolved in 150ml of water. Each of this experimental run was carried out for 8 days.

3.6. EXPERIMENTAL SETUP

For the anaerobic laboratory scale batch digester setup, the apparatus used in the setup process was two Buchner flask pipes of cork and a measuring cylinder. The method for biogas volume determination during this experiment was the volume displacement method. For each set up, one of the Buchner flasks served as the anaerobic digester in which the digestion takes place and biogas is produced and passes through the side arm of the Buchner flask. The top of the Buchner flask is sealed with a cork to prevent produced biogas from escaping out of the Buchner flask. On the side arm of the Buchner flask, a silicone pipe is attached to transport the produced gas to a second Buchner flask (which would contain water) and the pipe is connected to the second Buchner flask through the cork on the second Büchner flask which was drilled at exactly the diameter of the pipe. After this, a pipe is connected from the side arm of the second Büchner flask to a measuring cylinder where the volume of the gas can be measured based on the volume of water in the cylinder. Twelve setups were used in this experiment.

Plate 3. 7: Experimental setup

3.7. OPTIMIZATION

For optimization purposes, after completion of all experiments conducted according to the experimental design, the experimental data were systematically incorporated into the simplex lattice design model to determine the optimal conditions yielding maximum methane content, minimal CO_2/H_2S content, and maximum biogas yield.

In the experimental design of this work, Response Surface Methodology aided in the quantification of the controllable input parameters relationship with the obtained results. RSM is used in optimization for creating approximation models based on physical experimented observation, thus reducing the number of experimental runs needed to provide enough information for statistically acceptable results. In these twelve experimental setups, categorical and numerical factors were considered using one experimental design factor in RSM.

3.7.1. STATISTICAL DATA ANALYSIS

The statistical tool employed in analyzing the performance of the developed model was ANOVA. The interaction between the process parameters and the response of different regression models developed for the five substrates combinations was investigated. R2 represents the quality of the fitted polynomial quality, while F-test was employed to check the statistical significance, using Design Expert version 6. Finally, the model terms were considered using P-value, at a 95% confidence level.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

This chapter presents and discusses experimental results from optimizing biogas production using a ternary blend of cassava peel, yam peel, and potato peel co-digested with cow dung. A simplex lattice mixture design was used to investigate substrate ratio effects on biogas yield, methane concentration, and CO_2/H_2S composition. Results include proximate analysis of cow dung inoculum, optimization outcomes from 12 experimental runs, and mechanistic substrate interaction interpretations.

4.1 PHYSICAL AND CHEMICAL ANALYSIS OF COW DUNG

4.1.1 PROXIMATE ANALYSIS

Table 4. 1 Physical properties of Cow Dung

Property	Value (%)

Ash content	15.58%
Moisture content	84.59%
Volatile matter	73.48%
Carbon content	29.31%

1. Ash content

The ash content was calculated and the value gotten was 15.58%. The ash content obtained was 15.58% and it represents moderate inorganic mineral residue, providing essential macro- and micronutrients for anaerobic microorganisms. Ash-derived minerals including calcium, phosphorus, potassium, iron, and nickel serve as enzyme cofactors and pH buffers, enhancing process stability and methanogenic activity (Perämäki et al., 2025). Recent research demonstrates that optimal ash addition (10-20%) improves methane production by supplementing trace elements and buffering capacity without causing heavy metal inhibition (Elsayed et al., 2025). The observed level supports robust microbial metabolism while avoiding excessive sludge accumulation, making cow dung an ideal co-substrate for co-digestion systems.

2. Moisture content

The weight of the dried sample of cow dung is 1.06 g. The moisture content was calculated and the value gotten was 84.59%. The cow dung moisture content of 84.59% is optimal for anaerobic digestion, facilitating slurry formation and microbial activity. High moisture content (>75%) enhances hydrolysis by promoting enzyme diffusion and substrate accessibility, which is critical for lignocellulosic material degradation (Wani et al., 2025.). Additionally, adequate moisture ensures proper mixing, prevents stratification, and dilutes inhibitory metabolites such as ammonia and volatile fatty acids, thereby maintaining process stability (Qian et al., 2025.). The observed value requires minimal water addition, reducing operational costs while maintaining suitable organic loading rates for efficient biogas production.

3. Volatile matter

The weight before drying was 2.07 g and the weight after heating was 0.549 g. The volatile matter was calculated and the value gotten was 73.48%. The volatile matter content of 73.48% on a dry basis indicates excellent biodegradability, as most organic components are accessible for microbial conversion. High volatile matter (>70%) correlates positively with biochemical methane potential, providing abundant fermentable substrates including carbohydrates, proteins, and lipids for sequential anaerobic digestion stages (Oliveira et al., 2025). This high volatile matter confirms cow dung's dual functionality as both microbial inoculum and biodegradable co-substrate. The substantial volatile organic content facilitates rapid hydrolysis and acidogenesis, supporting efficient methanogenesis and maximizing biogas yields (Kelif Ibro et al., 2024b).

4. Fixed Carbon

Therefore, the fixed carbon was calculated and the value obtained was 29.31%. Fixed carbon content of cow dung substrate was determined as 29.31% through proximate analysis, wherein fixed carbon values ranging from 29.6% to 31.9% have been documented for various biomass materials including cow dung in hydrothermal liquefaction studies (Legesse et al., 2024). Fixed carbon represents residual carbonaceous material remaining after volatiles removal, consisting primarily recalcitrant organic compounds including crystalline cellulose, lignin, aromatic structures resisting rapid microbial degradation. Composite briquettes developed from cow dung biochar exhibited fixed carbon contents ranging 15.9%-44.6%, demonstrating substantial variation dependent upon processing conditions (Chen et al., 2022).

Cattle dung possesses higher ash and fixed carbon contents compared to agricultural residues like rice husk, with proximate analysis indicating cattle dung's elevated fixed carbon significantly influences energy value and power generation potential (Dai et al., 2025). The obtained value (29.31%) aligns closely with documented ranges, confirming lignocellulosic composition characteristic of cow dung biomass wherein aromatic compounds exhibit thermal and biological stability requiring extended retention periods for complete degradation during thermochemical or biological conversion processes.

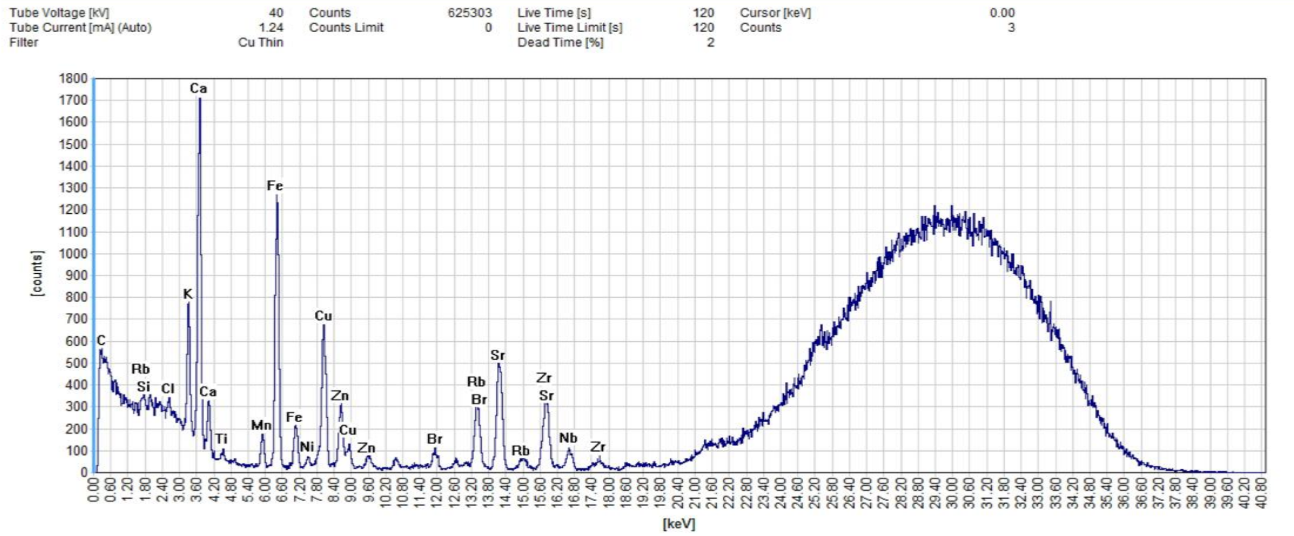

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Figure 4. 1: Elemental composition of cow dung

Table 4. 2: Chemical properties of cow dung

Element	Symbol	Conc. (wt%)
Iron	Fe	1.33826
Copper	Cu	0.169534
Nickel	Ni	0.154667
Zinc	Zn	0.13744
Aluminum	Al	0.965262
Magnesium	Mg	0.818835

Element	Symbol	Conc. (wt%)
Sulphur	S	2.617724
Phosphorus	P	9.617422
Calcium	Ca	36.19687
Potassium	K	14.64652
Manganese	Mn	0.258215
Rubidium	Rb	0.075835
Strontium	Sr	0.082389
Bromine	Br	0.041195
Nitrogen	N	3.885392
Chromium	Cr	5.62E-05
Tungsten	W	1.08791
Bismuth	Bi	2.190799
Barium	Ba	4.192478
Lead	Pb	2.696368
Tin	Sn	2.808717
Silicon	Si	14.79258
Niobium	Nb	1.039225
Tantalum	Ta	0.186312

The physicochemical analysis of cow dung revealed its suitability as an inoculum for biogas production. The elemental composition showed significant concentrations of calcium (36.20%), silicon (14.79%), and potassium (14.65%), which are essential nutrients for methanogenic bacteria. The presence of calcium is particularly important as it helps buffer the pH of the digestion system, preventing acidification that could inhibit methanogens. The nitrogen content of 3.89% provides adequate protein for microbial growth, while phosphorus (9.62%) and potassium serve as vital macronutrients supporting cellular metabolism and enzymatic activities during anaerobic digestion.

The detection of trace elements including iron (1.34%), zinc (0.14%), nickel (0.15%), and cobalt (though in minute quantities) is crucial, as these metals act as cofactors for key enzymes involved in methanogenesis. Iron, for instance, is essential for the formation of ferredoxin, a protein involved in electron transfer during the conversion of organic matter to methane. The Fourier-transform infrared spectroscopy (FTIR) analysis confirmed the presence of functional groups characteristic of organic compounds in cow dung, indicating the availability of biodegradable substrate alongside its role as microbial inoculum.

4.2. EXPERIMENTAL RESULT FOR BIOGAS YIELD

The experimental results shown in table 4.3 demonstrated significant variations in biogas yield depending on the substrate composition. Run 3, consisting of pure yam peel (10g), produced the highest biogas yield of 180 ml/50g.week, closely followed by Run 9 (also pure yam peel) with 174 ml/50g.week. This superior performance of yam peel can be attributed to its favorable carbohydrate composition, particularly its high starch and reducing sugar content, which serves as readily available substrates for hydrolytic and acidogenic bacteria. The consistency between Runs 3 and 9 (replicate runs) validates the reproducibility of the experimental procedure.

Cassava peel, when used alone (Run 1), yielded 98.4 ml/50g.week, demonstrating moderate biogas production potential. This relatively lower yield compared to yam peel may be due to the presence of cyanogenic glycosides in cassava peel, which can inhibit microbial activity at certain concentrations. However, the cassava peel still produced substantially more biogas than potato peel alone (Run 4: 70 ml/50g.week), suggesting that cassava peel possesses better biodegradability characteristics under the experimental conditions employed.

The binary mixture of yam and cassava peels (Run 10: 5g each) generated 147.5 ml/50g.week, indicating a synergistic effect where the combination performed better than cassava alone but lower than yam peel alone. This suggests that blending substrates can help balance nutrient availability and optimize C:N ratios for microbial communities. Conversely, the combination of yam and potato peels (Run 11: 5g each) produced only 25 ml/50g.week, the lowest yield among all experimental runs. This antagonistic effect could be explained by unfavorable pH conditions, nutrient imbalance, or the accumulation of volatile fatty acids that inhibited methanogenic activity.

The ternary mixture with equal proportions (Run 7: 3.33g each) yielded 41.2 ml/50g.week, performing poorly compared to most other combinations. This suggests that equal blending does not necessarily optimize biogas production, and that substrate-specific ratios must be carefully determined through experimental design.

4.3. STATISTICAL ANALYSIS OF BIOGAS PRODUCTION

ANOVA was employed to investigate Biogas volume yield using the quadratic model, which was deemed fit for the optimization. Table 4.3. Summarizes Biogas yield, methane concentration and CO_2/H_2S concentration for 12 experimental runs, from the various substrate combinations. The criteria for accepting regression (quadratic) model relied mainly on F- and P-values, where the former would compare the developed regression mean square value to the residual mean square. According to Hossain et al. (2017), a developed model can be considered to be reliable and reproducible when F- and P-values are high and low, respectively. Experimental data consists of different mixture ratio of Yam peels, potato peels and cassava peels, with Biogas yield. The data were analyzed using multiple regression techniques for developing an RSM model. A Special Quartic model for biogas yield and Quadratic models for methane and CO2/H2S concentrations. was developed and tested for accuracy, using R2 value. ANOVA was performed on the data, to determine the significance level of the substrates mixed in different ratios, at $p<0.05$ (95%)

4.3.1. BIOGAS YIELD BY ANALYSIS OF VARIANCE

The Model F-value of 203.59 indicates that the model is statistically significant. There is only a 0.05% chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate model terms are significant. Values greater than 0.1000 indicate the model terms are not significant, in this case, AB, AC, BC, A^2BC, ABC^2 and AB^2C made a significant model term. The Lack of Fit F-value of 1.76 implies the Lack of Fit is not significant relative to the pure error. There is a 31.56% chance that a Lack of Fit F-value this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit.

Table 4. 3: Experimental result of biogas yield

RUN	A: Yam peel (g)	B: Cassava peel (g)	C: Potato peel (g)	Biogas yield (ml/50g. week)	Methane Conc. (%)	CO_2/H_2SConc. (%)
1	0	10	0	98.4	86.7	13.3
2	6.66667	1.66667	1.66667	63	79.4	20.6
3	10	0	0	180	88.2	11.8
4	0	0	10	70	82.5	17.5
5	1.66667	1.66667	6.66667	69	74.5	25.5
6	1.66667	6.66667	1.66667	67	77.6	22.4
7	3.33333	3.33333	3.33333	41.2	75.3	24.7
8	0	5	5	31	71.9	28.1
9	10	0	0	174	84.5	15.5
10	5	5	0	147.5	87.9	12.1
11	5	0	5	25	70.2	29.8

12	0	10	0	93.5	82.9	17.1

For this model,

A = Yam peel

B = Cassava peels

C = Potato peels

The Predicted R^2 of 0.6735 is not as close to the Adjusted R^2 of 0.9933 as one might normally expect, i.e., the difference is more than 0.2. This may indicate a large block effect or a possible problem with your model and/or data. Things to consider are model reduction, response transformation, outliers, etc. All empirical models should be tested by doing confirmation runs. Adequate Precision measures the signal-to-noise ratio. A ratio greater than 4 is desirable. Precision ratio of 40.322 indicates an adequate signal. This model can be used to navigate the design space.

Final Equation in Terms of L_Pseudo Components

$$Biogasyield(ml/50g) = 177.18A + 96.13B + 70.36C + 46.27AB - 392.20AC - 206.10BC - 4177.32A^2BC - 1043.52AB^2C + 4510.19ABC^2\text{m}$$

The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. By default, the high levels of the mixture components are coded as +1, and the low levels are coded as 0. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

Table 4. 4: Biogas volume yield Analysis of variance (ANOVA) for special Quartic model

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	

Model	30640.38	8	3830.05	203.59	0.0005	significant
(1)Linear Mixture	16081.74	2	8040.87	427.43	0.0002	
AB	107.98	1	107.98	5.74	0.0962	
AC	7031.07	1	7031.07	373.75	0.0003	
BC	1941.57	1	1941.57	103.21	0.0020	
A^2BC	1711.78	1	1711.78	90.99	0.0024	
AB^2C	106.82	1	106.82	5.68	0.0974	
ABC^2	1968.65	1	1968.65	104.65	0.0020	
Residual	56.44	3	18.81			
Lack of Fit	26.43	1	26.43	1.76	0.3156	not significant
Pure Error	30.01	2	15.00			
Cor Total	30696.82	11				

Table 4. 5: Biogas Yield Fit Statistics

R^2	**0.9982**
Adjusted R^2	0.9933
Predicted R^2	0.6735
Adequate **Precision**	40.3223
Std. Dev.	4.34
Mean	88.30
C.V. %	4.91

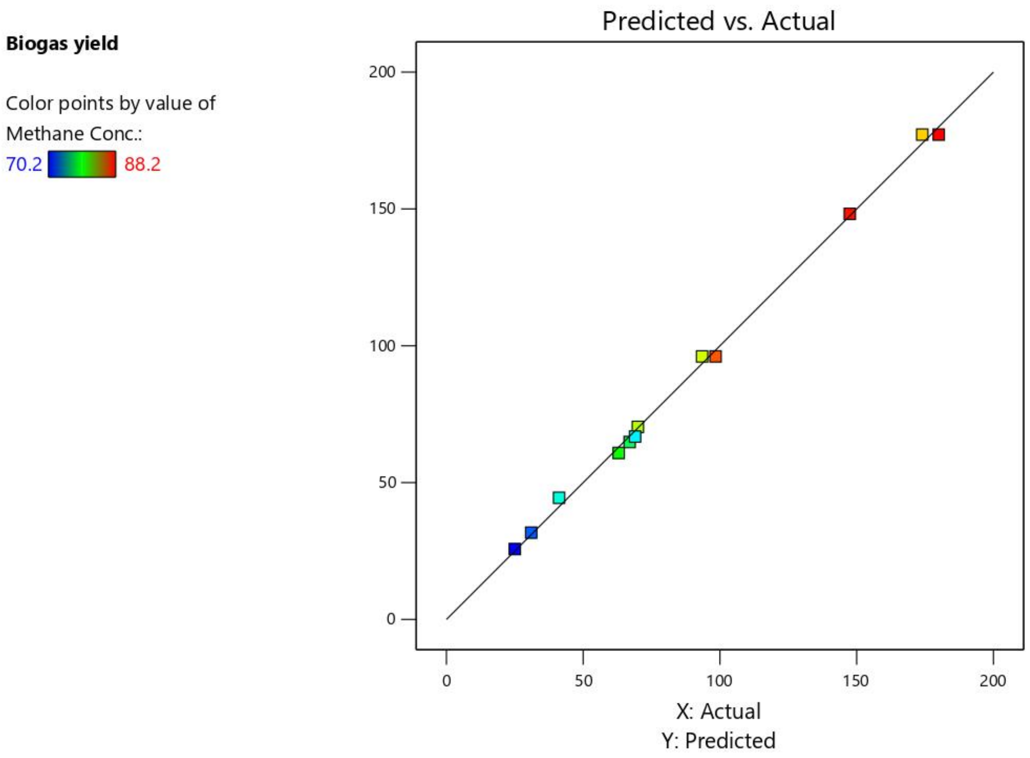

Figure 4. 2: Graph of Actual Biogas Volume Yield vs Predicted Biogas Volume

4.3.2. METHANE CONCENTRATION ANALYSIS OF VARIANCE (ANOVA)

The Model F-value of 23.98 indicates that the model is statistically significant. There is only a 0.07% chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate model terms are significant. Values greater than 0.1000 indicate the model terms are not significant, in this case, AC and BC, made a significant model term. If there are many insignificant model terms (excluding those required to support the hierarchy), model reduction may improve your model. The Lack of Fit F-value of 0.23 implies the Lack of Fit is not significant relative to the pure error. There is a 90.23% chance that a Lack of Fit F-value this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit.

The Predicted R^2 of 0.7444 is in reasonable agreement with the Adjusted R^2 of 0.9126; i.e., the difference is less than 0.2. Adequate Precision measures the signal-to-noise ratio. A ratio greater than 4 is desirable. The adequate precision ratio of 12.789 indicates an adequate signal. This model can be used to navigate the design space.

Final Equation in Terms of L_Pseudo Components

$$Methane\ Conc.\ (ppm) = 86.32A + 84.51B + 82.91C + 9.63AB - 53.98AC - 45.66BC$$

Table 4.6 Methane concentration Analysis of variance (ANOVA) for quadratic model

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	
Model	408.88	5	81.78	23.98	0.0007	significant
(1)Linear Mixture	136.53	2	68.26	20.02	0.0022	
AB	5.85	1	5.85	1.72	0.2382	
AC	164.10	1	164.10	48.12	0.0004	
BC	117.44	1	117.44	34.44	0.0011	
Residual	20.46	6	3.41			
Lack of Fit	6.40	4	1.60	0.2274	0.9023	not significant
Pure Error	14.06	2	7.03			
Cor Total	429.35	11				

Table 4.7: Methane Conc. Fit Statistics

R^2	**0.9523**
Adjusted R^2	0.9126
Predicted R^2	0.7444
Adequate Precision	12.7892
Std. Dev.	1.85
Mean	80.13
C.V. %	2.30

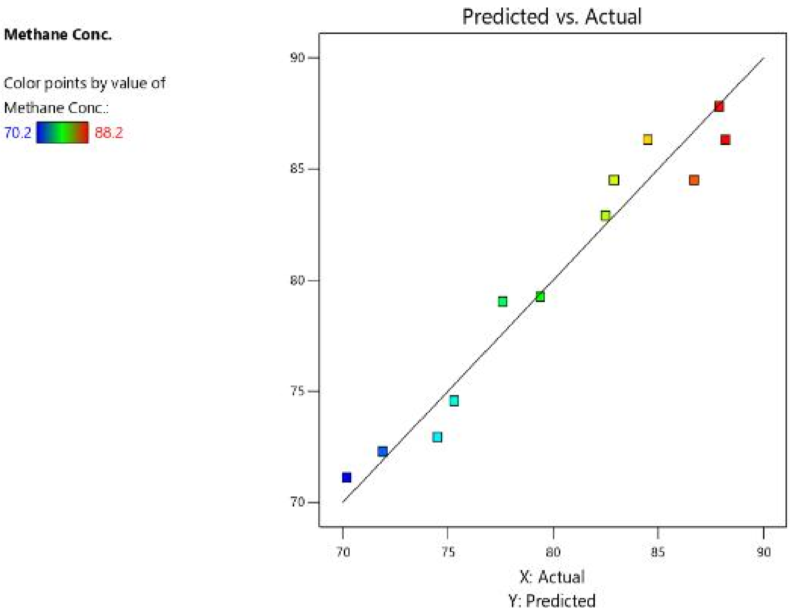

Figure 4.3: Graph of actual methane concentration vs predicted methane concentration

4.3.3. CO_2/H_2S CONCENTRATION ANALYSIS OF VARIANCE

The Model F-value of 23.98 indicates that the model is statistically significant. There is only a 0.07% chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate model terms are significant. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (excluding those required to support the hierarchy), model reduction may improve your model. The Lack of Fit F-value of 0.23 implies the Lack of Fit is not significant relative to the pure error. There is a 90.23% chance that a Lack of Fit F-value this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit.

The Predicted R^2 of 0.7444 is in reasonable agreement with the Adjusted R^2 of 0.9126; i.e., the difference is less than 0.2. Adequate Precision measures the signal-to-noise ratio. A ratio greater than 4 is desirable. Your ratio of 12.789 indicates an adequate signal. This model can be used to navigate the design space.

Final Equation in Terms of L_Pseudo Components

$$CO_2/H_2S(ppm) = 13.68A + 15.49B + 17.09C - 9.63AB + 53.98AC + 45.66BC$$

Table 4. 6: CO_2 /H_2S concentration Analysis of variance (ANOVA) for quadratic model

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	408.88	5	81.78	23.98	0.0007	significant
(1)Linear Mixture	136.53	2	68.26	20.02	0.0022	significant
AB	5.85	1	5.85	1.72	0.2382	Not significant
AC	164.10	1	164.10	48.12	0.0004	significant
BC	117.44	1	117.44	34.44	0.0011	Significant-
Residual	20.46	6	3.41			
Lack of Fit	6.40	4	1.60	0.2274	0.9023	not significant
Pure Error	14.06	2	7.03			
Cor Total	429.35	11				

Table 4. 7: CO_2 /H_2S Fit Statistics

R^2	0.9523
Adjusted R^2	0.9126
Predicted R^2	0.7444
Adequate Precision	12.7892
Std. Dev.	1.85
Mean	19.87
C.V. %	9.30

4.4. EFFECTS OF MIXTURE RATIO ON THE RESPONSE ANALYSIS

4.4.1. EFFECTS ON BIOGAS VOLUME YIELD

The 3D surface plots were generated from the predicted model equation and were used to comprehend the mixture ratio interaction effects for maximum yield of biogas volume. From the analysis of the plot, blend of higher ratio of yam pees yielded higher volume and as the ratio of biogas compared to others and according to Owamah et al. (2025), yam peels balanced starch and fiber profile enhances process stability, reducing the risk of inhibition seen in cassava-heavy blends also, yam peel's ability to elevate yields by 20–30% in mixtures due to their balanced C/N ratio, which avoids inhibition seen in potato or cassava-heavy systems (Okonkwo et al., 2018). The graph of the, the maximum biogas yield occurred in the mixture containing only yam peels 10g of yam peels, 0g of cassava peels and 0g of potato peels.

4.4.2. EFFECTS ON METHANE YIELD

A 3D response plot and a ternary mixture diagram from the 3D response plot and the ternary mixture plot diagram, which was generated from the modeled equation, the yield of methane increased as the proportion of yam peels increased in the blend. According to (Odedina et al., n.d.), yam peels have an optimal C/N ratio, which enhances methanogenic bacterial growth when paired with cow dung. yam peels low lignin content reduces microbial inhibition, boosting methane yield compared to cassava or potato peels (Nweke et al., n.d.). From the response plot, the maximum methane concentration was gotten from yam peel alone. Which yielded 88.2% of methane.

Figure 4. 3: 3D response surface plot for biogas yield

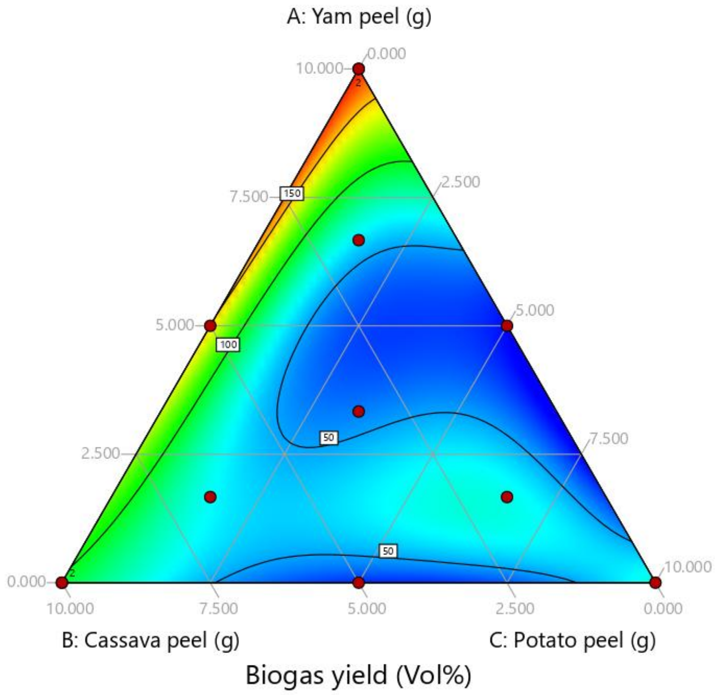

Figure 4. 4: Ternary Mixture plot for biogas yield

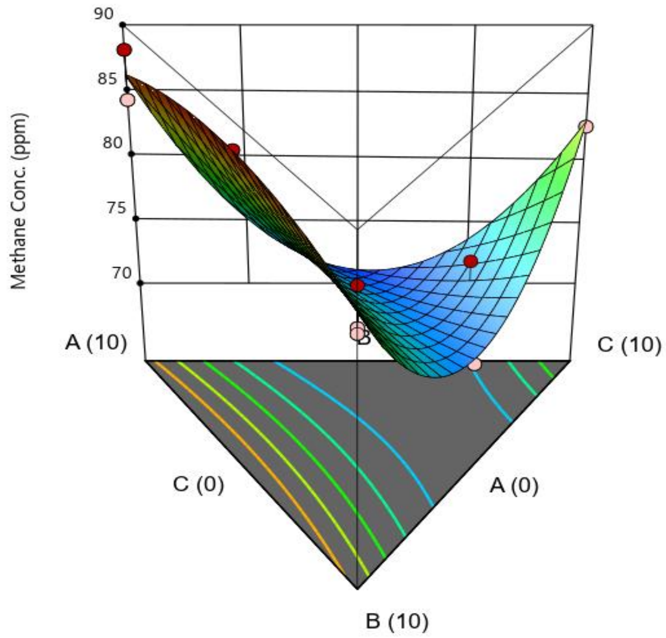

Figure 4. 5: 3D response surface plot for methane concentration

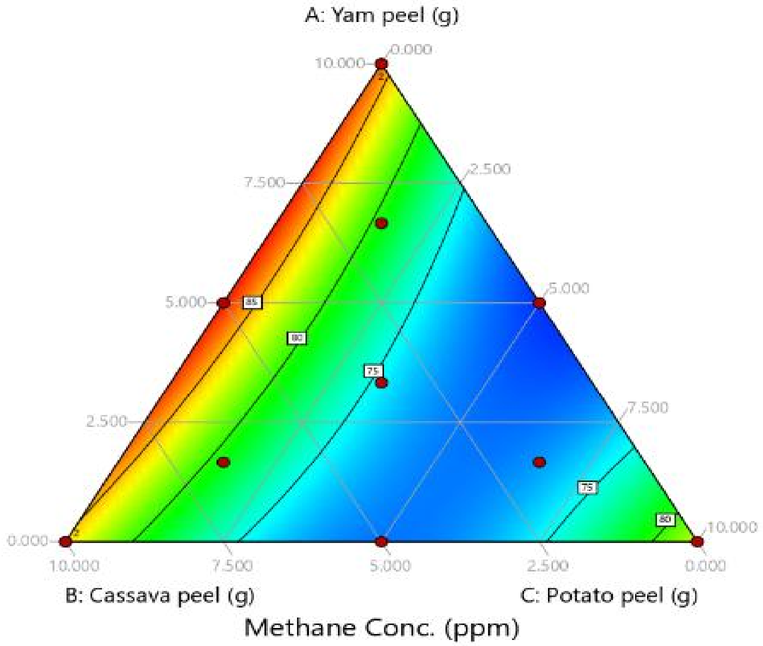

Figure 4. 6: Ternary Mixture plot for biogas yield

4.4.3. EFFECTS ON CO_2/H_2S CONCENTRATION

The 3d surface plots, and ternary plots were generated from the predicted model equation and was used to comprehend the mixture ratio interaction effects on yield of co2/h2s yield. The co2/h2s concentration was seen to decrease as the ratio of yam peels in the mixture this from an increase in the ratio of yam peels leads to an increase in the methane yield which, which leads to a decrease in the concentration of co2/h2s.

4.5. BIOGAS OPTIMIZATION RESULT

From the table above, the optimal mixture ratio of yam peels to potato peels to cassava peeks was 6.66667:1,66667:1.66667. The resulting volume, methane concentration and CO_2/H_2S concentration of the biogas were 60.835ml, 79.253% and 20.747% respectively.

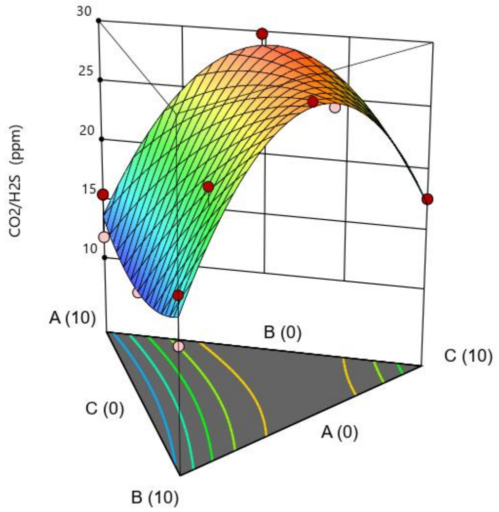

Figure 4. 7: 3D response surface plot for CO_2/H_2S concentration

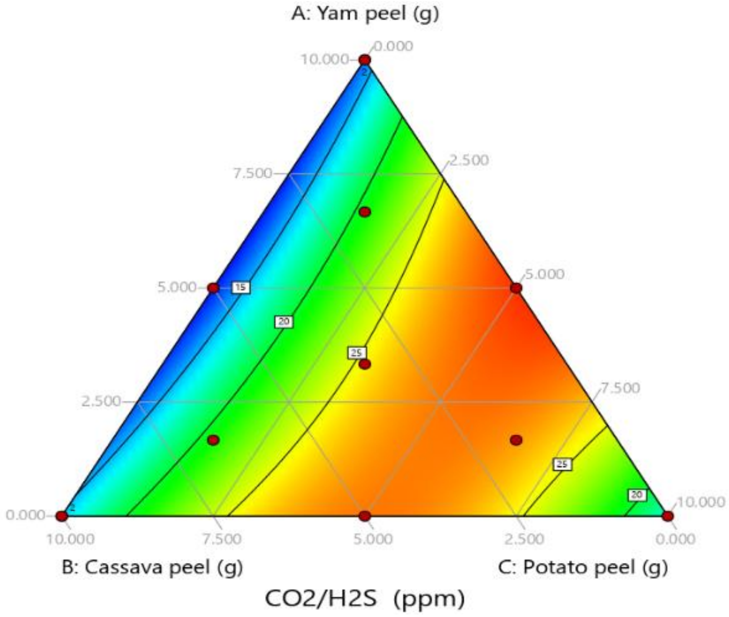

Figure 4. 8: Ternary Mixture plot for CO_2/H_2S concentration

.

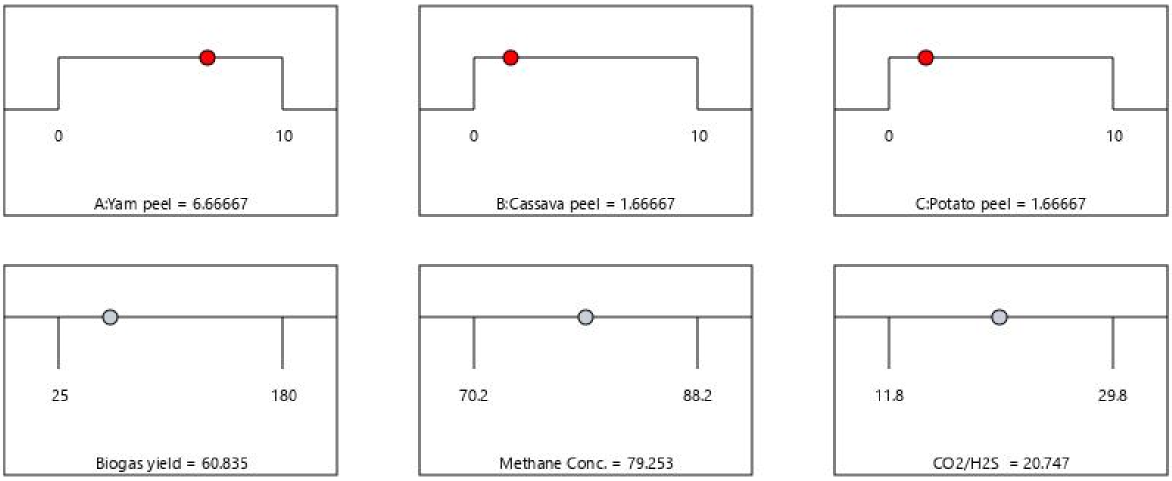

Figure 4. 9: Optimum biogas generation condition

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

This study successfully investigated the optimization of biogas production from blends of cassava, yam, and potato peels using cow dung as inoculum through a simplex lattice mixture design approach. The physicochemical characterization of cow dung confirmed its suitability as an inoculum, revealing significant concentrations of essential nutrients including calcium (36.20%), potassium (14.65%), phosphorus (9.62%), and nitrogen (3.89%), alongside trace elements that serve as cofactors for methanogenic enzymes.

The experimental results demonstrated that substrate composition significantly influences both biogas yield and methane concentration. Pure yam peel emerged as the superior feedstock, producing the highest biogas yield of 180 ml/50g.week with an excellent methane concentration of 88.2%. This performance substantially exceeded that of cassava peel (98.4 ml/50g.week, 86.7% CH_4) and potato peel (70 ml/50g.week, 82.5% CH_4) when used individually. The binary mixture of yam and cassava peels (5g each) exhibited synergistic effects with a yield of 147.5 ml/50g.week and high methane content of 87.9%, while the yam-potato combination showed strong antagonistic interactions, producing only 25 ml/50g.week.

Statistical analysis through ANOVA confirmed the validity of the developed models, with the Special Quartic model for biogas yield showing excellent fit ($R^2 = 0.9982$, F-value = 203.59, $p < 0.0005$) and the Quadratic model for methane concentration demonstrating good predictive capability ($R^2 = 0.9523$, F-value = 23.98, $p = 0.0007$). The regression equations derived from this study provide reliable tools for predicting biogas yield and gas quality based on substrate composition, with adequate precision values exceeding the minimum threshold, indicating their utility for process optimization.

The significant negative interaction coefficient for yam-potato combinations (-392.20) in the biogas yield equation explains the poor performance of these blends, likely due to pH imbalances, nutrient antagonism, or volatile fatty acid accumulation. Conversely, the favorable performance of yam-cassava blends suggests complementary substrate characteristics that enhance microbial activity and methane production. Overall, this research demonstrates that strategic blending of agricultural waste can optimize biogas production, with substrate-specific ratios being critical for maximizing both yield and methane quality.

5.2 RECOMMENDATIONS

Based on the findings of this study, the following recommendations are proposed:

For Industrial Application:

1. Prioritize yam peel as the primary feedstock for biogas plants in regions where it is abundantly available, given its superior performance in both yield and methane quality.
2. Implement yam-cassava peel blends at optimized ratios (predominantly yam peel with 20-30% cassava peel) to enhance process stability while maintaining high biogas production rates.
3. Avoid or minimize potato peel inclusion in substrate mixtures, particularly in combination with yam peel, due to demonstrated antagonistic effects on biogas yield.

For Further Research:

1. Conduct kinetic studies to understand the mechanisms underlying the antagonistic interaction between yam and potato peels, including investigation of inhibitory compounds and pH dynamics during digestion.
2. Extend the study to include different retention times, temperatures, and organic loading rates to establish comprehensive operational parameters for scaled-up systems.
3. Investigate the co-digestion of optimized peel blends with other agricultural wastes such as livestock manure, food waste, or crop residues to further enhance biogas yield and process stability.
4. Perform economic feasibility analysis and life cycle assessment of biogas production from optimized substrate blends to evaluate commercial viability and environmental benefits.
5. Examine the digestate quality resulting from optimized substrate mixtures for potential application as organic fertilizer, thereby creating a circular economy approach.
6. Study the effects of pretreatment methods (thermal, chemical, or biological) on the biogas potential of individual peels and their blends to maximize substrate degradability.

For Policy and Implementation:

1. Develop guidelines for small-scale biogas systems in rural communities based on locally available agricultural waste, using the predictive models developed in this study.
2. Promote awareness among farmers and agro-processors about the energy potential of agricultural peels and the importance of proper waste segregation for optimal biogas production.

3. Encourage the establishment of decentralized biogas facilities near cassava, yam, and potato processing centers to minimize transportation costs and maximize waste-to-energy conversion efficiency.

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APPENDIX

1. Ash content

$$\%Ash = \frac{Mass.of.Ash}{Mass.of.Sample} \times 100$$

Equation 3.1

$$\%\mathrm{Ash} = \frac{0.522}{3.3507} \times 100$$

Ash content = 15.58%

2. Moisture content

$$\%Moisture = \frac{A-B}{A} \times 100$$

Equation 3.2

$$\%\mathrm{Moisture} = \frac{6.88-1.06}{6.88} \times 100$$

Moisture content = 84.59%

3. Volatile Matter

$$\%V_m = \frac{(M_m - M_v)}{M_s} \times 100$$

Equation 3.3

$$\%\mathrm{V_m} = \frac{2.07-0.549}{2.07} \times 100$$

Volatile matter content = 73.48%

4. Fixed carbon content

$$\%\mathrm{FC} = \frac{Mass\ after\ carbonization}{Mass\ before\ carbonization} \times 100$$

Equation 3.4

$$\%\mathrm{FC} = \frac{0.296}{1.01} \times 100$$

Fixed carbon content = 29.31%