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EDITORIAL

The Energy Commission of Nigeria (ECN) was established by Act 62 of 1979 and its subsequent amendments with the responsibility for the strategic planning and coordination of national policies in the field of energy in all its ramifications. In doing so, the Commission serves as a centre for gathering and dissemination of information relating to national policy in the field of energy development; collates, analyzes and publishes information relating to the field of energy from all sources; and makes recommendations for the exploitation of new sources of energy to the Government. Accordingly, the Energy Commission of Nigeria publishes the JOURNAL OF ENERGY POLICY, RESEARCH AND DEVELOPMENT (JEPRD) in accomplishing part of its mandate.

JEPRD serves as the vehicle for dissemination of research and developmental efforts and policies on energy in Nigeria as well as from other parts of the world deemed relevant to Nigeria's energy development. The Journal is published bi-annually with the main objective of bringing together research findings and policy strategies in all aspects of energy and also to serve as a forum for energy experts to provide, receive and exchange information to foster the growth and better utilization of energy in all its ramifications.

This edition features ten scholarly articles highlighting critical developments across the energy sector. The first paper is on the adoption of Compressed Natural Gas (CNG) in Nigeria's transport sector, which assesses the potential environmental and economic benefits of shifting to cleaner gaseous fuels for mobility.

The second paper examines Hydrogen Energy, providing a comprehensive overview of global developments, emerging technologies, associated challenges, and the prospects for Nigeria's participation in the hydrogen economy.

The third paper focuses on the development and testing of a Pyrolysis Machine, aimed at promoting sustainable waste-to-energy conversion, improved waste management, and alternative fuel generation.

The fourth paper is on modelling inflow into Shiroro Hydropower Station using an Artificial Neural Network (ANN), offering tools for improved hydropower resource planning and operational forecasting.

The fifth paper investigates performance measures for multi-class imbalanced data classification, an essential dimension of energy systems modelling and predictive analytics.

The sixth paper presents the design and performance evaluation of a Reversed Absorber-Enhanced Passive Indirect Solar Dryer, demonstrating improvements in drying efficiency for agricultural and renewable energy applications.

The seventh paper is on the Dual-Function Biomass Rocket Stove, a locally developed clean cooking solution supporting thermal efficiency and reduced biomass consumption.

The eighth paper reviews the future perspectives of Compressed Natural Gas (CNG) research in Nigeria, identifying priority areas for innovation, policy reform and national deployment.

The ninth paper examines biodiesel production using waste frying oil and copper oxide nanoparticles catalyst, evaluating how variations in oil-to-methanol ratio influence the quality and yield of the biodiesel produced.

The tenth paper presents an Assessment of Water Quality for Small Hydropower Development along the Rima River, providing essential hydrological and environmental data for future hydropower projects.

The Commission remains committed to the timely publication of the journal. In no distant time, all transactions of the journal will fully be online. You are, therefore, encouraged to continue to submit your articles for possible publication.

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ADVANCING LOW-CARBON MOBILITY: ADOPTION OF COMPRESSED NATURAL GAS (CNG) IN NIGERIA'S TRANSPORT SECTOR

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Abstract: Compressed Natural Gas (CNG) presents a cleaner and more cost-effective alternative to conventional fuels such as gasoline and diesel, making it a viable option for Nigeria's transportation sector. However, its adoption faces significant challenges, particularly in public perception and safety concerns. This review evaluates these dual issues, emphasizing their impact on CNG implementation and its potential to drive Nigeria's energy transition. Limited awareness of CNG's economic and environmental advantages contributes to consumer and business hesitation, while misconceptions about safety—such as fears of explosions and cylinder durability—further inhibit adoption. Drawing on global experiences, the review highlights strategies to enhance public acceptance through targeted education campaigns, demonstration projects, and pilot programs. Engineering solutions addressing safety concerns, including robust cylinder standards, pressure relief devices, leak detection systems, and periodic maintenance protocols, are identified as essential for mitigating risks related to high-pressure storage and refueling infrastructure. This review also underscores the broader benefits of CNG adoption, including significant reductions in greenhouse gas emissions and air pollution, aligning with global climate goals. Economically, CNG offers long-term cost savings for vehicle operators, though infrastructural deficits and high conversion costs remain barriers. In view of the above, the study recommends policy interventions, fiscal incentives, and public-private partnerships to build a supportive ecosystem for CNG deployment. By addressing public perception and safety concerns while leveraging Nigeria's abundant natural gas reserves, CNG can play a pivotal role in reducing fuel costs, promoting sustainable energy practices, and advancing the country's environmental and energy security objectives.

Keywords: Compressed Natural Gas, Conventional fuels, Limited awareness, Safety misconceptions

1. INTRODUCTION

Over the years, petroleum fuels have served as a significant energy source for the transportation industry. The usage of fossil fuels, including petroleum, has witnessed a notable increase over the years, driven by factors such as population growth and evolving consumer lifestyles [1]. Various types of alternative fuels are being considered worldwide to cater to the harmful effects of fossil fuels and meet the ever-growing industrial and domestic demand. The global push toward sustainable development and climate change mitigation has heightened the demand for low-carbon solutions across various sectors. The transportation sector in Nigeria remains a significant contributor to greenhouse gas (GHG) emissions due to its reliance on fossil fuels. Transitioning to compressed natural gas (CNG) as an alternative fuel offers a promising pathway for achieving low-carbon mobility, improving air quality, and reducing the nation's carbon footprint [2&3]. CNG represents a distinct technology that repurposes natural gas

typically utilized in households, plants, factories, and other settings as vehicular fuel. This is achieved through compressing the gas and storing it in a pressurized container, facilitating its use as a clean and efficient alternative fuel for vehicles [4].

Road transport dominates Nigeria's mobility landscape, contributing significantly to the gross domestic product (2.7%) while being heavily reliant on gasoline and diesel-powered internal combustion engines (ICEs) [5]. Passenger vehicles, which constitute the bulk of Nigeria's transport fleet, are responsible for a large share of transport emissions and thus represent a critical target for decarbonization. In 2018, Nigeria's road vehicle composition comprised commercial vehicles (57.7%), private vehicles (40.98%), and government or diplomatic vehicles (1.32%) [2].

Despite being an oil-dependent economy, generating 9% of GDP from crude oil exports, Nigeria has significant opportunities for low-carbon

transport through its vast natural gas reserves (187 trillion cubic feet) [6] and renewable energy potential [7&8]. The adoption of CNG vehicles, already successful in countries like India, Pakistan, and Brazil, is feasible and aligns with Nigeria's energy profile [9-11]. However, barriers such as limited infrastructure, low electricity access and high poverty rates (affecting 60% of the population) pose challenges to swift transitions to advanced solutions like electric vehicles [12-13]. For example, a World Bank report revealed that 85 million Nigerians don't have access to electricity from the national grid [12].

Nigeria's dependency on imported petroleum products further complicates the transport sector's sustainability, making it vulnerable to global oil price shocks. Passenger transportation accounts for 77% of fossil fuel consumption in Nigeria, highlighting the potential impact of transitioning this segment to CNG or other locally sourced energy alternatives [2]. With the country ranking as the 7th highest gas-flaring nation, emitting 17.76 Mt of CO₂ annually, leveraging its underutilized natural gas reserves for CNG adoption could address environmental and economic inefficiencies [14].

Globally, CNG is recognized as a cleaner alternative fuel, with significantly lower emissions of CO₂, nitrogen oxides (NO_x), and particulate matter than conventional fuels [15]. In Nigeria, the Presidential CNG Initiative launched in October 2023 underscores the government's commitment to reducing reliance on petroleum fuels while providing affordable energy solutions [2]. Despite these efforts, challenges such as insufficient infrastructure, safety concerns, and high vehicle conversion costs continue to hinder widespread adoption. To overcome these obstacles and realize the benefits of CNG adoption, Nigeria must invest in expanding CNG

infrastructure, enforce stringent safety standards, and raise public awareness about the environmental and economic advantages of CNG-powered vehicles. Drawing lessons from countries with successful CNG programs, such as Argentina and Germany, and integrating these insights into local strategies could accelerate Nigeria's transition to a low-carbon transport future.

The aim of this review article is to critically evaluate the prospects, challenges, and policy frameworks associated with the adoption of Compressed Natural Gas (CNG) as a viable low-carbon alternative in Nigeria's transport sector. By synthesizing insights from global best practices and local context-specific analyses, this article seeks to highlight the environmental, economic, and social implications of transitioning to CNG. It further explores Nigeria's abundant natural gas reserves, infrastructure gaps, and regulatory frameworks, offering strategic recommendations for scaling up CNG adoption to promote sustainable mobility, reduce greenhouse gas emissions, and enhance energy security.

2. GLOBAL TRENDS IN CNG ADOPTION

Transportation is a cornerstone of economic systems at local, regional, and global levels, driving the movement of goods and people. However, it also consumes substantial energy, vital for enhancing accessibility and diversifying transport modalities [16].

In many developed economies, transportation accounts for between 6% and 12% of the GDP. The sector spans various modes, including land (passenger cars, freight, buses, and motorcycles), air, rail, and sea, each demanding specific energy sources for propulsion [17]. While transportation facilitates socio-economic development, it poses significant environmental challenges, such as emissions, noise, pollution, and health risks [18]. The International Energy Agency (IEA) highlights transportation as the

second-largest source of global carbon emissions after electricity generation, contributing 23% of emissions and consuming 61.2% of the world's oil [18&20]. Environmental impacts are assessed using carbon intensity (gCO₂e/MJ), energy intensity (MJ/km), and total transportation demand (km) [21]. Compressed Natural Gas (CNG) is emerging as a viable alternative fuel in transportation, offering reductions in greenhouse gas emissions, improved air quality, and enhanced energy security. Its role in advancing low-carbon mobility is particularly critical in natural gas-rich countries [17].

Transportation accounted for 29% of global energy use in 2015, with petroleum products comprising 96% of the energy consumed, representing 65% of the total global oil consumption [22]. In 2019, the global final energy use by transport mode was dominated by road transport, with significant contributions from aviation and shipping (Fig. 3). Consequently, the sector emitted over 7 billion tonnes of CO₂, or roughly one-quarter of global emissions. Road transport dominates energy consumption, using 75% of the sector's energy and generating 80% of its CO₂ emissions, with passenger vehicles responsible for 75% of this demand (IRENA, 2018). Natural Gas Vehicles (NGVs) are increasingly adopted worldwide due to climate change concerns, energy security, and the need to reduce dependence on traditional fossil fuels. More than 100

countries possess natural gas reserves, though two-thirds of production is concentrated in the USA, Russia, Iran, Qatar, and China [23]. Optimizing natural gas exports remains vital, particularly in nations like Spain, which rely on imports due to negligible production [23].

The global CNG market is projected to grow at a compound annual growth rate (CAGR) of 6.5% between 2023 and 2030, driven by stringent environmental policies, increased alternative fuel adoption, and advancements in CNG infrastructure (Figs. 1-3). Major economies, including the USA, India, and China, integrate CNG into energy strategies, significantly increasing its use in transportation and industry [17]. In 2019, the global Total Energy Supply (TES) was approximately 14,282 Mtoe annually (Browne and Chan, 2011). Therefore, the transition from oil to electric drives and to synthetic fuels and biofuels is key to achieving the goals of the Paris Climate Agreement. The international commitment to decarbonization, highlighted by the 2021 United Nations Climate Change Conference (COP26), includes achieving net-zero emissions by 2050. The Clydebank Declaration, signed by 19 countries during COP26, pledged to establish six decarbonized "green corridors" for zero-emission vessels by 2025 [24]. The adoption of CNG is integral to reducing transportation emissions, aligning with global climate goals. As nations transition to low-carbon economies, CNG serves as a sustainable alternative to fossil fuels, supporting international efforts to mitigate climate change and achieve net-zero targets.

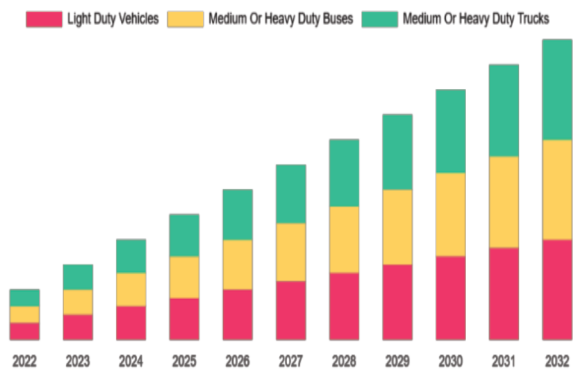


Fig 1. Global Compressed Natural Gas (CNG) Market 2023-2032 (By End User) [25].

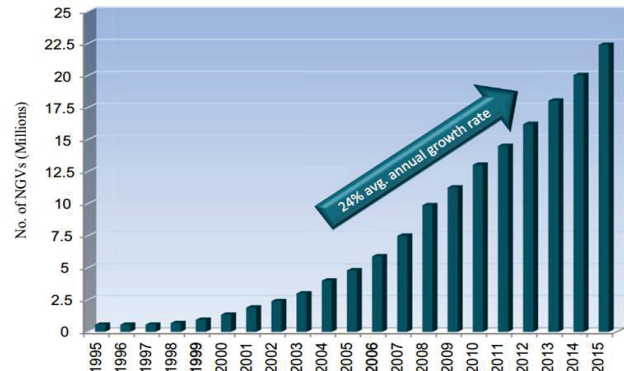


Fig. 2. Worldwide growth of NGV's between 1995 – 2015 [25].

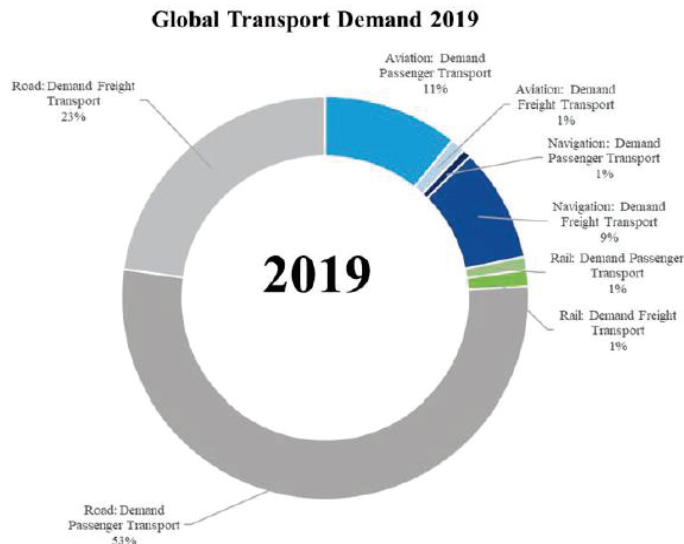


Fig 3. Global final energy use, by transport mode, in 2019 (without international aviation or navigation bunker fuels) [17].

3. CNG ADOPTION IN SUB-SAHARAN AFRICA

The transportation sector across Sub-Saharan Africa is experiencing a significant transformation as more countries embrace sustainable energy solutions, with Compressed Natural Gas (CNG) playing a key role in this shift. This change is driven by the region's abundant natural gas resources, the urgent need to cut greenhouse gas emissions, and the desire for greater energy security. According to Mordor Intelligence [26], the market for CNG and Liquefied Petroleum Gas (LPG) vehicles in Africa is forecast to grow from USD 1.37 billion in 2025 to USD 1.90 billion by 2030, reflecting a compound annual growth rate (CAGR) of 6.78%. This growth highlights the increasing recognition of the economic and environmental advantages of alternative fuels across the continent.

In Nigeria, the successful adoption of CNG as a mainstream fuel source for transportation hinges on several critical factors. Central to this are government policies and regulatory frameworks. The removal of the petroleum subsidy in 2023 by the Federal Government of Nigeria has indeed encouraged the rapid adoption of CNG as an alternative fuel. This shift is driven by the need for more affordable and sustainable energy solutions in the face of rising petrol (gasoline) prices. A carbon tax also encourages a shift to CNG by raising the cost of conventional fuels like gasoline and diesel, making CNG a more affordable and eco-friendlier alternative. Moreover, the introduction of stringent emissions standards has further spurred high-emission cities like Lagos to adopt cleaner energy options, including CNG. This trend aligns with global efforts to reduce urban air pollution and mitigate climate change impacts.

Egypt has emerged as a regional leader in CNG adoption, largely due to comprehensive government initiatives. The Egyptian government's vehicle conversion program aims to convert 2,600 vehicles per month, supported by incentives, low-interest loans, and strategic partnerships. For instance, Gastec has teamed up with Eni to develop multi-energy fueling stations, providing CNG alongside traditional fuels. Additionally, Egypt has made significant investments in CNG infrastructure, establishing a network of refueling stations and vehicle conversion centers, further boosted by tax breaks and subsidies. This integrated approach has enabled Egypt to lead the continent in CNG adoption, setting a benchmark for other nations. Nigeria, as Africa's largest economy, is also making considerable progress in promoting CNG as a cleaner transportation energy source. The Nigerian government aims to convert one million vehicles to CNG by 2025, with plans to roll out 11,500 CNG buses and distribute 55,000 conversion kits [27]. The government also intends to establish 50 electric vehicle (EV) charging stations in major cities such as Lagos, Abuja, and Port Harcourt [28]. This initiative not only seeks to tackle urban air pollution but also aims to reduce the country's reliance on imported petroleum. Furthermore, Nigeria's rich natural gas reserves present a strategic advantage, positioning CNG as both a cost-effective and sustainable alternative.

In South Africa, while electric vehicles (EVs) have been at the forefront of the country's energy transition, CNG is increasingly being integrated into the transport system. Johannesburg's Metrobus fleet now includes over 150 CNG-powered buses, aligning with national efforts to reduce carbon emissions and operational costs. Public transportation systems across South Africa are gradually adopting cleaner fuels, driven by government incentives and strategic partnerships aimed at expanding infrastructure. This dual approach, focusing on both electric and CNG vehicles, highlights South Africa's commitment to diversifying

its energy mix while addressing environmental challenges.

Kenya has launched pilot projects to convert public service vehicles (PSVs) to CNG as part of its broader strategy to improve air quality and reduce transportation costs [29]. These projects demonstrate the government's commitment to sustainable energy solutions. Similarly, Tanzania is making strides in expanding its CNG infrastructure with the construction of a TSh 14 billion mother station, which will serve as a central hub for gas distribution to smaller stations nationwide [30]. This initiative is designed to overcome logistical challenges and increase access to natural gas, particularly in regions with limited.

In Morocco, the government is pushing forward with its ambitious energy transition strategy, which includes a target to achieve 52% renewable energy in its energy mix by 2030. As part of this transition, Morocco

plans to convert 10,000 taxis to CNG by 2025, supported by government grants and collaborations with private sector stakeholders [31]. This initiative underscores Morocco's proactive approach to reducing urban air pollution and promoting cleaner energy, further solidifying its leadership in renewable energy adoption in the region. The adoption of CNG in Sub-Saharan Africa is becoming a key strategy to address environmental, economic, and energy security challenges. Countries such as Nigeria, Egypt, and South Africa are at the forefront, demonstrating the potential for CNG to transform the region's transportation sector. By expanding infrastructure, fostering supportive policies, and promoting cross-border collaboration, Africa can continue to make strides toward a more sustainable and energy-secure future. Plate 1 shows CNG-powered Innoson Vehicle Manufacturing (IVM) buses, evidence of transformative stride of the present administration in the energy sector.



Plate 1: A line of CNG-powered Innoson Vehicle Manufacturing (IVM) buses

4. DRIVERS OF CNG UTILIZATION IN AUTOMOBILES

The adoption of Compressed Natural Gas (CNG) as an alternative fuel for automobiles in Nigeria hinges on several

key drivers. Government policy and regulatory support play a crucial role. A carbon tax system incentivizes the shift to CNG by raising the cost of conventional fuels like gasoline and diesel through the removal of subsidies, positioning CNG as a more affordable and environmentally friendly option. Additionally, higher fuel emissions standards compel high-emission cities such as Lagos to adopt cleaner alternatives.

Government subsidies, tax exemptions for CNG vehicles, and the establishment of a specialized agency such as Presidential CNG Initiative (Pi-CNG) to oversee CNG infrastructure and fuel pricing further accelerate this transition.

Infrastructure development drives CNG adoption significantly. The establishment of CNG refueling stations in urban centers and high-traffic areas ensures accessibility. Public-private partnerships expedite the deployment of these stations, while a national gas transmission and distribution network lowers transportation costs and boosts CNG availability. Mobile refueling stations and CNG vehicle conversion centers would address accessibility challenges and support vehicle conversions.

Public awareness and education build consumer confidence. Awareness campaigns highlight the economic and environmental benefits of CNG, such as reduced fuel costs and lower emissions. Training programs and workshops dispel misconceptions and educate Nigerians on the health and environmental advantages of switching to CNG. These efforts emphasize CNG's role in achieving Nigeria's climate goals.

Economic incentives make CNG an appealing option. Its lower cost compared to gasoline and diesel attracts private and commercial vehicle owners. Financial incentives, such as subsidies for vehicle conversions, further ease the financial burden on consumers. Partnerships with local automakers to produce CNG vehicles domestically reduce costs and stimulate the local automotive industry.

Private sector participation plays a pivotal role in CNG sector growth. The government

incentivizes private investment through tax breaks and reduced import duties for CNG-related equipment. Public-private partnerships develop critical infrastructure, including refueling stations and conversion centers, fostering innovation and bolstering CNG's viability in Nigeria.

Technological advancements in CNG vehicle engines and fueling systems enhance adoption. Bi-fuel and dual-fuel vehicles, operating on both gasoline and CNG, simplify the transition for consumers. Research focuses on improving CNG engine efficiency and vehicle performance, making CNG-powered vehicles more attractive. Smart metering and monitoring systems at refueling stations ensure accurate billing and fuel usage tracking, boosting consumer confidence.

The environmental and health benefits of CNG further drive its adoption. CNG emits fewer greenhouse gases and particulate matter compared to gasoline and diesel, reducing air pollution and improving air quality. This improves public health outcomes in Nigeria's congested urban areas by mitigating respiratory and cardiovascular diseases linked to pollution. International collaboration facilitates CNG adoption in Nigeria. By learning from countries such as India and China with successful CNG programs, Nigeria can implement proven best practices. Partnerships with international organizations bring technical expertise and funding to support large-scale CNG infrastructure projects. The successful adoption of CNG in Nigeria relies on effective government policy, robust infrastructure development, economic incentives, private sector involvement, technological advancements, and international collaboration as shown in Table 1. By addressing these key drivers, Nigeria transitions to a cleaner, more sustainable transportation system that benefits both the environment and the economy.

Table 1: key drivers for the adoption of Compressed Natural Gas (CNG)

Key Driver	Description
Government Policy and Regulatory Support	Introduction of carbon tax systems, stricter fuel emissions standards, and government subsidies for CNG vehicles.
Infrastructure Development	Establishment of CNG refueling stations, expansion of natural gas transmission and distribution networks, and development of conversion centers.
Public Awareness and Education	Awareness campaigns highlighting the benefits of CNG, training programs on the health and environmental advantages of switching to CNG.
Economic Incentives	Financial incentives such as subsidies for vehicle conversion, lower taxes for CNG vehicles, and partnerships with local automakers to reduce costs.
Private Sector Participation	Encouraging private investments through tax breaks, reduced import duties, and public-private partnerships to build infrastructure.
Technological Advancements	Promotion of bi-fuel/dual-fuel vehicles, improvement of CNG vehicle engines for better performance, and smart metering systems for refueling stations.
Environmental and Health Benefits	Reduction in greenhouse gas emissions and air pollution, leading to better public health outcomes, particularly in urban areas.
International Collaboration	Learning from successful CNG programs in other countries, leveraging international technical expertise, and accessing funding for CNG projects.

5. THE ROLE OF THE ENERGY COMMISSION OF NIGERIA IN ADVANCING CNG ADOPTION

The Energy Commission of Nigeria (ECN) plays a crucial role in advancing the adoption of Compressed Natural Gas (CNG) as part of its broader Energy Transition Program. By leveraging Nigeria's vast natural gas reserves, the ECN helps promote sustainable energy utilization, reduce dependency on petroleum products, and facilitate the transition to cleaner fuels. One of ECN's primary functions is to formulate and coordinate energy policies that prioritize CNG adoption. It works closely with other government agencies to

create roadmaps aimed at reducing reliance on petroleum products while optimizing Nigeria's natural gas resources. These policies ensure that CNG becomes a key part of Nigeria's energy mix. The ECN also tackles technical and logistical challenges related to CNG through its research and development initiatives. The National Centre for Energy and Environment (NCEE), a key research hub under the ECN, is focused on enhancing CNG storage, bottling, and distribution systems. The center is also procuring cost-effective vehicle conversion kits for training Micro, Small, and Medium Enterprises (MSMEs) on transitioning to CNG. Additionally, pilot projects are conducted by the Centre to test the practicality of CNG technologies in real-world scenarios. Infrastructure development is another vital area for the ECN. The commission is collaborating with private sector stakeholders to establish vehicle

conversion centers to facilitate the retrofitting of conventional vehicles to run on CNG, thereby making it more accessible to consumers. Capacity building and public education are key components of the ECN's strategy. The commission organizes technical training programs to equip professionals with the necessary skills for the CNG sector. Public awareness campaigns are also held to inform the Nigerian public about the economic and environmental benefits of CNG, encouraging wider adoption. The ECN actively engages in partnerships with federal and state governments, private investors, and international organizations. These collaborations help secure investments, technical expertise, and provide incentives such as tax benefits for CNG infrastructure and vehicle conversion. These efforts aim to foster a vibrant and sustainable CNG sector in Nigeria.

To ensure the success and sustainability of its initiatives, the ECN conducts environmental and economic impact assessments. These studies highlight the positive effects of CNG adoption, such as reductions in greenhouse gas emissions, improvements in urban air quality, and cost savings from reduced fuel imports. The ECN's specialized research centers contribute significantly to advancing CNG adoption. For instance, the NCEE conducts environmental impact assessments, the National Centre for Energy Efficiency and Conservation (NCEEC) focuses on energy-efficient CNG use, and the National Centre for Petroleum Research and Development (NCPRD) optimizes natural gas applications to improve the cost-effectiveness of CNG. Through these efforts, the ECN has made significant strides in reducing urban air pollution, enhancing energy security, and creating jobs within the CNG value chain. With continued government support, private sector involvement, and international collaboration, the ECN is leading

Nigeria's transition to cleaner and more sustainable energy solutions.

6. COMPOSITION AND COMPARATIVE ANALYSIS OF CNG, LPG, DIESEL, PETROL AND KEROSENE

CNG predominantly consists of methane (CH_4), making up 70–98% of its volume. It is derived from natural gas reserves and compressed to approximately 3,600 psi for storage and transport. Methane, the primary energy source in CNG, is a simple hydrocarbon with one carbon atom and four hydrogen atoms (fig 4), providing a high calorific value. Other components like ethane (C_2H_6), carbon dioxide (CO_2), nitrogen (N_2), and water vapor may be present in trace amounts, depending on the source and processing of the gas. CNG includes tert-butyl mercaptan, an additive that gives it a distinctive odour for leak detection. Its boiling point for methane is -161.5°C , making it gaseous at ambient temperatures, and its density under standard conditions is around 0.72 kg/m^3 , with an energy content of roughly 50 MJ/kg . The fuel has a flammability range of 5–15% in air and an autoignition temperature of approximately 540°C , which, combined with low emissions of CO_2 and NO_x , positions it as a clean-burning and environmentally friendly fuel.

In contrast, LPG primarily comprises propane (C_3H_8) and butane (C_4H_{10}), produced as a by-product of crude oil refining or extracted from natural gas streams. These hydrocarbons give LPG high energy density and flammability, essential for various applications. Propane's three carbon atoms contribute to its volatility and energy output, while butane, with four carbon atoms, provides stability at lower temperatures. LPG may also contain trace hydrocarbons like ethane (C_2H_6), propylene (C_3H_6), and butylene (C_4H_8), which influence its combustion properties. LPG includes ethyl mercaptan as an odorant for leak detection. It has a boiling point range from -42°C for propane to 0°C for butane, depending on the composition. Its density is about 2.5 kg/m^3 in

gaseous form and 500–580 kg/m³ in liquid form, with an energy content of around 46 MJ/kg. LPG has a flammability range of 2.1–9.5% in air and an autoignition temperature of approximately 470°C, making it efficient and manageable for domestic, industrial, and vehicular uses. The distinct physico-chemical properties of CNG and LPG (Table 2) underscore their suitability for different applications. LPG, with its high energy density, low boiling point, and ease of liquefaction, is ideal for domestic and industrial purposes. Meanwhile, CNG's high methane content offers exceptional environmental benefits, requiring high-pressure storage for optimal use.

Combustion efficiency plays a critical role in determining the performance of these fuels, reflecting how effectively their energy content is converted into usable energy. Comparing the combustion efficiency of CNG, LPG, and kerosene highlights their unique characteristics and applications (Table 3). CNG exhibits high combustion efficiency due to its clean-burning nature, producing minimal particulate matter, carbon monoxide (CO), and nitrogen oxides (NO_x). This makes it a preferred choice for reducing air pollution and greenhouse gas emissions, with lower engine maintenance costs due to reduced soot and sludge

formation. LPG also demonstrates efficient combustion, generating fewer emissions compared to diesel and petrol. Its combustion produces CO₂ and water vapor, with minor quantities of CO and NO_x. Although its emissions are slightly higher than CNG, they are significantly lower than those of gasoline and diesel.

Diesel combustion, known for its higher efficiency, benefits from diesel engines' higher compression ratios. However, diesel produces more pollutants, including NO_x and particulate matter, due to higher combustion temperatures and pressures.

Petrol combustion is less efficient than diesel, generating higher levels of CO and hydrocarbons due to incomplete combustion, especially in poorly regulated air-fuel mixtures. This contributes to smog formation and urban air pollution. Kerosene combustion occurs at moderate temperatures, producing CO₂, water vapor, and CO. However, its lower efficiency compared to LPG and CNG results in higher emissions of particulate matter and sulfur oxides (SO_x), raising concerns about air quality and health risks when used in residential heating and cooking.

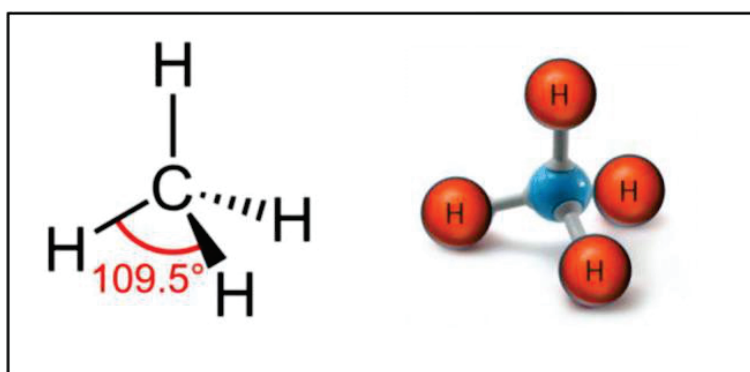


Fig 4: CH₄ and its structure

Table 2: Composition and Properties of CNG and LPG

Property	LPG	CNG
Composition	Propane (C_3H_8) and butane (C_4H_{10})	Mainly methane (CH_4)
Physical State	Liquid under pressure	Gas at room temperature, compressed to ~3,600 psi
Energy Content (MJ/kg)	~46	~50
Density	~2.5 kg/m ³ (gas) or 500–580 kg/m ³ (liquid)	~0.72 kg/m ³ (at standard conditions)
Boiling Point (°C)	-42 to -0.5	-161.5 (methane)
Flammability Range (% in Air)	2.1–9.5	5–15
Autoignition Temperature (°C)	~470	~540
Storage and Handling	Stored as liquid in pressurized cylinders	Stored as gas in high-pressure cylinders
Combustion Efficiency	High	Very high
Emissions	Lower CO ₂ , NO _x , and particulate matter	Very low CO ₂ , NO _x , and particulate matter
Odour	Added odorant (ethyl mercaptan)	Added odorant (tert-butyl mercaptan)
Applications	Cooking, heating, automotive fuel	Automotive fuel, industrial use
Safety	Highly flammable Denser than air, can accumulate in low areas	Lighter than air, disperses quickly Non-toxic but flammable
Cost	Moderate	Low

Table 3: Comparative Analysis of Combustion Efficiency of CNG, LPG, Diesel, Petrol and Kerosene

Fuel Type	Combustion Efficiency (%)	Key Factors Influencing Efficiency
CNG	90–95%	- High hydrogen-to-carbon ratio - Homogeneous combustion - Low carbon deposits
LPG	85–90%	- Controlled air-fuel mixture - Lower boiling point - Complete combustion achievable
Diesel	75–85%	- Compression ignition - Variable fuel quality - Combustion chamber design
Petrol (gasoline)	70–80%	- Spark ignition - High volatility - Tendency for incomplete combustion
Kerosene	65–75%	- Lower volatility than petrol - Tendency for incomplete combustion - High carbon residue

7. GOVERNMENT SUPPORT AND POLICY INITIATIVES TO CATALYZE CNG VEHICLES IN AFRICA

Government support and policy initiatives are pivotal in driving the adoption and growth of CNG vehicles across Africa. Recognizing the economic, environmental, and energy security advantages of transitioning to CNG, many African governments have implemented comprehensive strategies to promote this alternative fuel (Table 4). These efforts include financial incentives, regulatory measures, infrastructure development, and ambitious adoption targets to accelerate the integration of CNG vehicles into national transportation systems. One notable example is Nigeria's ambitious goal to deploy 1 million CNG vehicles by 2027 as part of its broader strategy to reduce reliance on imported fuels and lower greenhouse gas emissions. This target includes the immediate deployment of 11,500 CNG-powered buses and the provision of 55,000 conversion kits to retrofit existing vehicles for CNG

use. Such initiatives demonstrate a structured approach to scaling up CNG adoption, combining direct action with enabling policies.

Financial incentives are a cornerstone of many government strategies to encourage CNG adoption. These incentives often include tax breaks, subsidies for vehicle purchases, or financial assistance for retrofitting existing vehicles with CNG capabilities. These measures lower the economic barriers for individuals and businesses, making the switch to CNG more attractive and feasible. Additionally, several African governments have set clear, ambitious targets for CNG adoption, providing a roadmap for industry stakeholders and signaling long-term commitment to cleaner fuels.

Regulatory frameworks also play a critical role in this transition. Policies that mandate or incentivize the use of cleaner fuels in public transportation and government fleets have spurred demand for CNG vehicles. By focusing on sectors with high visibility and impact, such as public transit systems, governments can lead by example and demonstrate the feasibility of CNG as a sustainable alternative.

Infrastructure development is another key area of focus. Many African nations are investing in CNG refueling networks, often through public-private partnerships. The expansion of this infrastructure is essential to overcome one of the primary barriers to CNG adoption – the limited availability of refueling stations. By ensuring reliable access to CNG refueling facilities, governments can significantly enhance the practicality and convenience of using CNG vehicles. However, the success of these government initiatives varies across the continent. Countries with abundant natural gas resources, such as Nigeria and Egypt, and a strong commitment to reducing urban air pollution have generally been more effective in promoting CNG adoption. Conversely, nations with

limited resources or inconsistent policy implementation have faced challenges in achieving similar progress.

The sustainability and long-term impact of these initiatives depend on several factors, including consistent implementation, regular policy reviews, and adaptations to evolving market conditions. Governments must strike a delicate balance between environmental goals and economic realities, ensuring that policies remain financially viable while fostering significant environmental benefits. Collaborative efforts with the private sector, robust monitoring mechanisms, and public awareness campaigns will be crucial in sustaining the momentum for CNG adoption and driving Africa towards a cleaner and more energy-secure future.

Table 4: Some recent Government Initiatives for CNG Vehicles in Africa Countries

Country	Time Period	Key Government Initiatives for CNG Vehicle
Egypt	2021 – 2023	National initiative to convert 150,000 vehicles to CNG, with plans to expand refueling stations from 688 to 1,000
Nigeria	2023 – 2027	Target to deploy 1 million CNG vehicles by 2027, including immediate plans for 11,500 CNG buses and 55,000 conversion kits for existing vehicles
Morocco	By 2025	The Government plans to convert 10,000 taxis to CNG by 2025, supported by a combination of government grants and private sector partnerships
South Africa	Ongoing	Over 150 CNG buses operate in Johannesburg’s public transport sector, significantly reducing the city’s carbon footprint and fuel costs.
Kenya	Ongoing	Government and private sector initiatives to convert public service vehicles to CNG, aiming to reduce urban air pollution.
Tanzania	Ongoing	Launch of the country’s first integrated CNG filling station and conversion center, with plans for more stations to fuel 800 vehicles daily.
Egypt	2021 – 2023	National initiative to convert 150,000 vehicles to CNG, with plans to expand refueling stations from 688 to 1,000

8. CHALLENGES AND BARRIERS TO EFFECTIVE CNG ADOPTION IN NIGERIA

The adoption of Compressed Natural Gas (CNG) and Compressed Biogas (CBG) as alternative fuels for energy and transportation in Nigeria faces several significant challenges. These barriers largely stem from infrastructure limitations, technological constraints, safety concerns, and public awareness issues, which collectively hinder the widespread adoption of these fuels.

8.1 Infrastructure Development

8.1.1 Availability of Dispensing Stations

One of the most pressing challenges in the adoption of CNG in Nigeria is the limited number of refueling stations as reported by Nouni et al., [32]. The establishment of a comprehensive and reliable network of CNG dispensing stations is essential to ensure that vehicles using these fuels are adequately supported. However, the development of such infrastructure is uneven across Nigeria, with some parts of the country lacking sufficient refueling stations, especially in remote areas. At the moment, key operators like NIPCO Gas and Gastec Nigeria have established stations in cities including Lagos, Abuja, and Benin City etc. The availability and accessibility of dispensing stations are crucial for boosting consumer confidence in these fuels and encouraging adoption. To address this issue, government policies and private sector investments must prioritize the development of strategically located refueling stations in urban centers and along major transportation corridors [33]. Public-private partnerships and incentives are key to expanding this network and ensuring widespread availability.

8.1.2. Pipeline Infrastructure

The transportation of CNG is highly reliant on an extensive pipeline infrastructure that

delivers natural gas from production facilities to refueling stations [34]. However, the existing pipeline network in Nigeria is inadequate to meet the demands of the growing CNG market. Expanding and modernizing the pipeline infrastructure requires substantial investment and careful planning to ensure efficient and uninterrupted supply. The lack of sufficient pipeline capacity to handle increased demand could result in supply disruptions, ultimately impeding the growth of the CNG and CBG sectors. To overcome this barrier, significant investment in pipeline infrastructure, alongside regulatory support for its expansion, is necessary to ensure a consistent and reliable supply of natural gas for refueling stations [35].

8.2 Engine Range and Refueling Time

8.2.1. Limitations of CNG Vehicles

Another major challenge for the adoption of CNG and CBG is the limited driving range of vehicles that run on these fuels. Compared to traditional gasoline or diesel-powered vehicles, CNG and CBG vehicles tend to have a lower energy density, meaning they require larger storage tanks to achieve similar ranges [36]. The need for larger tanks can increase the weight of the vehicle and reduce available cargo space, making it less appealing for commercial applications, such as trucking or long-distance transportation. This limitation can be a significant deterrent for both individual and business consumers considering the switch to CNG vehicles. However, ongoing research and development efforts are focused on improving storage technologies and optimizing fuel efficiency to overcome these range constraints [37 & 38].

8.2.2. Technological Advances

Technological innovation plays a critical role in overcoming the range limitations of CNG and CBG vehicles. For instance, advancements in lightweight composite materials for storage tanks are helping increase fuel capacity without adding significant weight, thereby

improving vehicle performance [39]. Additionally, innovations in engine technology, such as more efficient combustion systems and advanced fueling infrastructure, are reducing refueling times and improving overall vehicle efficiency [40]. These advancements are making CNG and CBG vehicles more competitive with traditional fuel-powered vehicles, offering a viable and sustainable alternative for both personal and commercial transportation.

8.3. Awareness Campaigns

Awareness and public perception are crucial factors influencing the adoption of CNG and CBG in Nigeria. There are still widespread misconceptions regarding the safety, reliability, and environmental benefits of these fuels, which hinder their acceptance [41]. Many Nigerians remain skeptical about the practicality and safety of CNG often due to a lack of information on natural gas. To address this challenge, targeted public awareness campaigns are essential to educate the public about the benefits of these alternative fuels. These campaigns should focus on dispelling myths about the safety and reliability of CNG and CBG while emphasizing their positive impact on the environment, including the reduction of greenhouse gas emissions and the promotion of energy sustainability.

In addition to safety and environmental benefits, there is need for intensive public awareness which should highlight the economic advantages of adopting CNG and CBG, such as the reduction of fuel costs and the potential for job creation within the alternative fuel sector. Collaborative efforts between government agencies, environmental organizations, and industry stakeholders can help build public confidence and encourage more Nigerians to consider adopting CNG and CBG vehicles. By informing the public about these benefits and offering incentives, awareness campaigns can significantly contribute to the widespread adoption of CNG and CBG as clean, affordable, and reliable alternative fuels. Overcoming the

challenges and barriers to CNG and CBG adoption in Nigeria requires addressing infrastructure gaps, improving vehicle technology, and launching effective public awareness campaigns. Through strategic investments, technological innovations, and targeted educational initiatives, Nigeria can unlock the full potential of CNG and CBG as part of its broader energy transition agenda.

9. BENEFITS OF CNG AS AN AUTOMOBILE FUEL IN NIGERIA

Compressed Natural Gas (CNG) offers numerous advantages as an alternative fuel for vehicles in Nigeria. These benefits span environmental, economic, and safety domains, positioning CNG as a viable solution to the nation's energy and transportation challenges [42-44].

9.1. Reduction in Air and Noise Pollution from the Transport Sector

Gasoline and diesel-powered vehicles emit pollutants and particulate matter that pose serious health risks, such as stroke, heart disease, respiratory illnesses, and cancer. These concerns underscore the need for alternative fuels like Compressed Natural Gas (CNG), which emit fewer pollutants than conventional fuels (Dioha and Kumar, 2020). In another study, Oluwole et al. [45] identified high concentrations of hydrocarbon (HC), oxygen (O_2), and nitrogen oxides (NO_x) emissions on Lagos roads associated with Gasoline and diesel-powered vehicles, and hence recommends a shift to CNG as a more environmentally friendly fuel. CNG has been proven to reduce emissions of CO_2 by 23–35%, particulate matter (PM) to near-zero levels, NO_x by 87–90%, and HC by 67–76% [46, 47]. In Dhaka, transitioning to CNG led to improved air quality and reduced premature deaths [48]. Additionally, CNG vehicles produce less noise, reducing urban noise pollution [49].

9.2. Energy Security

CNG enhances energy security by reducing reliance on volatile and often scarce conventional fuels like gasoline and diesel [50]. Nigeria's frequent fuel shortages lead to inflated prices, disrupting economic activities, particularly in the transport sector. Adopting CNG mitigates these challenges, offering a stable, locally sourced fuel supply [51].

9.3. Increased Productivity

Energy access is pivotal for socio-economic development, and CNG, as a low-carbon fuel, supports increased productivity. Its cost-effectiveness reduces transportation expenses, facilitating easier mobility for Nigerians [52]. Furthermore, CNG is domestically sourced, unlike imported gasoline and diesel, conserving foreign reserves [50].

9.4. Cost-Effectiveness

CNG is substantially cheaper than gasoline and diesel, with cost reductions of approximately 76.8% and 62.9%, respectively [49-53]. For instance, Armenia reports that CNG is 3–4 times cheaper than gasoline and half the price of diesel. Economic analyses estimate annual savings of ₦411,408 for vehicles covering 100 km daily, with national savings potentially reaching ₦654 billion if CNG adoption is fully implemented [50 - 54]. A recent study shows that CNG adoption could reduce fuel costs by over ₦5,518 per 100 [40].

9.5. Enhanced Automobile Efficiency

CNG's high octane rating eliminates the need for antiknock additives like benzene or lead, contributing to cleaner combustion and lower emissions [55]. CNG vehicles demonstrate higher brake thermal efficiency (5–12% above gasoline vehicles) and longer service life due to reduced engine wear, improved spark plug longevity, and lower maintenance costs [49-54].

9.6. Safety Advantages

CNG's safety profile surpasses that of gasoline. It is less combustible, requiring a 5–15% concentration in air and a high ignition temperature of 680°C, compared to gasoline's 230–280°C [49]. CNG cylinders are more durable than gasoline tanks and less likely to ignite in accidents. Additionally, any CNG leakage dissipates quickly into the air, minimizing fire risks compared to pooled liquid fuels like gasoline [50]. kilometers compared to petrol, providing substantial economic relief to transport operators.

10. Safety Concerns Associated with CNG Usage in Nigeria

The explosion at the NipCo CNG filling station in Benin City highlights the urgent need to address safety challenges associated with compressed natural gas (CNG) usage in Nigeria (Plate 2A&B). CNG's high-pressure storage raises concerns about cylinder integrity, particularly due to the prevalence of substandard or counterfeit cylinders in the market. Poor transportation infrastructure and inadequate safety protocols further exacerbate these risks, increasing the likelihood of leaks or ruptures during transit. The limited access to certified CNG refueling stations in Nigeria forces users to rely on unregulated facilities, leading to unsafe practices such as overfilling and the absence of essential safety systems like gas detectors. Expanding access to properly certified refueling stations equipped with trained personnel and safety mechanisms is vital to minimizing risks.

A lack of public awareness and training on CNG safety measures remains a significant barrier. Many users are unfamiliar with proper handling, leading to unsafe practices like tampering with cylinders or failing to identify gas leaks. Targeted education campaigns and training programs for vehicle operators are essential to bridge this knowledge gap. The improper conversion of petrol or diesel vehicles

to CNG also poses risks, including leaks, engine damage, or fires. A shortage of skilled technicians and economic constraints further result in deferred maintenance, increasing the likelihood of system failures. High-quality conversion services and incentives for regular maintenance are critical to addressing these hazards.

Although CNG is less flammable than gasoline, it can still result in fires or explosions under certain conditions. Leaks in poorly ventilated spaces or high-impact collisions can compromise safety. Strengthening vehicle safety standards, such as requiring impact-resistant cylinders and automatic shut-off valves, can significantly reduce these risks. Nigeria's weak

regulatory frameworks and inconsistent enforcement undermine CNG safety standards. Substandard equipment and unregulated practices persist, eroding public confidence in CNG as a safe fuel alternative. Strengthening regulatory bodies, conducting routine inspections, and enforcing strict penalties for noncompliance are necessary steps to improve adherence to safety protocols. Addressing these challenges is critical to ensuring the safe adoption of CNG in Nigeria. Strengthened regulations, expanded infrastructure, enhanced public awareness, skilled workforce development, and improved emergency response systems will restore public confidence in CNG and unlock its potential as a viable alternative fuel.



Plate 2A&B: A car powered by Compressed Natural Gas, CNG, exploded at a NipCo CNG filling station in Benin City, the capital of Edo State

11. ADDRESSING PUBLIC CONCERNS AND PROMOTING SAFETY

The NipCo explosion in Benin City has highlighted the urgent need to address safety challenges associated with CNG usage in Nigeria as follows;

- Strengthening regulatory enforcement is critical, including the implementation of stringent manufacturing standards, regular audits of facilities and vehicles, and imposing penalties for noncompliance.
- Expanding certified infrastructure is equally important, with a focus on establishing more authorized refueling stations

equipped with trained personnel, gas detectors, and emergency response systems, while upgrading existing facilities to meet modern safety standards.

- Creating more public awareness: Public awareness campaigns must be launched to educate the public on CNG safety measures, emphasizing proper refueling practices, recognizing gas leaks, and understanding the risks associated with tampering with cylinders. Certification programs for vehicle operators and targeted community engagement initiatives can further bridge the knowledge gap.

- Improving emergency response systems is vital, involving the modernization of fire-fighting tools and gas detection equipment, alongside specialized training for responders to manage CNG-related incidents effectively. Clear incident management protocols must also be developed to ensure swift and coordinated actions during emergencies.
- More skilled workers: Skilled workforce development is essential for the safe conversion and maintenance of CNG vehicles. Comprehensive training programs for technicians, accreditation systems for workshops, and incentives for vehicle owners to perform regular maintenance can significantly reduce risks.

12. RECOMMENDATIONS FOR IMPLEMENTING COMPRESSED NATURAL GAS (CNG) AS AN AUTOMOBILE FUEL IN NIGERIA

The implementation of compressed natural gas (CNG) as an automobile fuel in Nigeria requires strategic policy recommendations.

First, the development of a targeted carbon tax system is critical. Research suggests that carbon taxes could reduce CO₂ emissions by 26.9% in Nigeria by 2050 [52]. Such policies would make gasoline and diesel more expensive, thus making CNG a more attractive alternative. Drawing inspiration from India, where high gasoline emissions forced cities to adopt CNG, Nigeria could mandate that high-emission cities transition to CNG [56].

Second, increasing the availability and accessibility of CNG refueling stations is essential for the adoption of CNG vehicles. Studies indicate that having CNG refueling stations amounting to at least 10% to 20% of conventional fuel stations would alleviate concerns about availability [54]. Reducing bureaucratic barriers to constructing and operating CNG refueling stations, such as providing lower permits, could incentivize private investment.

The government could also use its NNPC mega station initiative to establish CNG refueling stations in key locations and introduce mobile refueling stations to enhance access [47].

In addition, market-based policies are needed to encourage CNG adoption. Offering subsidies to reduce the cost of CNG, including lowering importation taxes on CNG equipment and refueling station operations, would widen the cost gap between CNG and conventional fuels [54]. Moreover, ensuring that investors see high returns and low risk in CNG investments could foster a more robust market, as seen in Pakistan where tax exemptions were crucial to the growth of CNG use [47].

Subsidizing vehicle conversion costs is another critical step. Providing loans or subsidies for converting vehicles from gasoline or diesel to CNG would make the transition more affordable for Nigerians. Collaboration with banks to offer interest-free loans for these conversions could boost adoption [54].

The introduction of bi-fuel or dual-fuel vehicles should be prioritized. These vehicles, which run on both CNG and gasoline, address CNG's limited range and frequent refueling requirements. Research shows that dual-fuel engines are 30-40% more efficient and reduce fuel consumption by 25% [57]. Nigeria could follow Pakistan's model and begin with dual-fuel vehicles to ease the transition.

There is also a need to assign responsibilities for CNG implementation. In countries like India, Argentina, and Brazil, agencies have been set up to promote CNG use [54]. Nigeria lacks such an agency, and as a result, there is limited policy development regarding gas utilization. The government should establish a CNG program, ensuring that responsibilities for station development and vehicle provision are clearly defined.

Another important factor is the development of a domestic gas transmission and distribution network. Nigeria should prioritize this domestic infrastructure over international

networks like the West African Gas Pipeline, as seen in Brazil and Argentina [54]. A robust domestic gas network would lower transport costs for CNG and incentivize the construction of more refueling stations.

Public awareness campaigns are crucial for the successful adoption of CNG. Many Nigerians are unfamiliar with CNG automobiles and their benefits. The government should invest in education programs to highlight the environmental and economic advantages of CNG over conventional fuels. Public awareness efforts could also include skill acquisition programs related to CNG vehicle maintenance and operation, helping to create jobs and build a skilled workforce in the CNG sector [57].

Reforming gas pricing is also necessary. Currently, domestic gas prices are significantly lower than export prices, encouraging gas export over domestic utilization [54]. By reforming the pricing system, the government could make gas more profitable for domestic use, cutting down on gas flaring and encouraging the use of CNG.

Partnering with indigenous automobile manufacturers, such as Innoson Vehicle Manufacturing Company, would reduce the cost of CNG vehicles. Local production of CNG vehicles would lower prices and make them more affordable to Nigerian consumers. The government should also fund research and development to optimize vehicle designs for the local market [54].

Finally, prioritizing the use of CNG in transit buses could be an effective strategy. By focusing on converting public transport buses to CNG, Nigeria could reduce both emissions and traffic congestion. This approach was successfully implemented in China, where CNG-powered buses led to reduced pollution and higher profitability for transit companies [58]. The successful implementation of CNG as an automobile fuel in Nigeria requires a multifaceted approach involving policy reform, infrastructure development, public

awareness, and collaboration with indigenous manufacturers. By learning from the experiences of countries like India, Pakistan, and Brazil, Nigeria can pave the way for a cleaner, more sustainable transportation future.

13. CONCLUSION

The adoption of Compressed Natural Gas (CNG) as an alternative automobile fuel in Nigeria presents a promising pathway towards reducing the country's reliance on gasoline and diesel, while also addressing environmental concerns such as air pollution and greenhouse gas emissions. The successful integration of CNG into Nigeria's energy and transport sectors hinges on a combination of strategic government policies, robust infrastructure development, private sector participation, and public awareness campaigns. Key drivers such as economic incentives, technological advancements, and international collaboration can catalyze the widespread adoption of CNG vehicles, making them more accessible and affordable for Nigerians.

Moreover, the implementation of supportive regulatory frameworks, such as carbon tax systems and subsidies, along with the establishment of an extensive CNG refueling network, will foster the growth of a sustainable CNG market. Encouraging private investments through favorable policies will also ensure that CNG infrastructure is built at scale across the country. While challenges remain, particularly in financing and infrastructure deployment, the collective effort of government bodies, private sector players, and local communities can pave the way for a cleaner, more efficient, and economically viable transportation system in Nigeria. Ultimately, the transition to CNG as an automobile fuel will not only support Nigeria's energy diversification goals but also contribute to broader global efforts to combat climate change and promote sustainable development.

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HYDROGEN ENERGY: GLOBAL TRENDS, POTENTIAL, CHALLENGES, AND THE NIGERIAN JOURNEY

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Abstract: Hydrogen energy is gaining significant attention as a key player in the global transition towards sustainable energy systems. As the most abundant element in the universe, hydrogen offers a clean, versatile energy carrier with the potential to reduce dependence on fossil fuels and mitigate environmental challenges such as climate change and air pollution. This review explores the current state of hydrogen energy, focusing on its role in the energy transition, key production methods, and technological advancements. The primary methods for hydrogen production, including steam methane reforming, electrolysis, and biomass conversion, are examined, with an emphasis on the growing importance of renewable hydrogen (green hydrogen) produced via electrolysis powered by renewable energy sources. Technological developments in hydrogen storage, transportation, and fuel cell applications are also discussed, highlighting the progress in improving efficiency and reducing costs. However, significant challenges remain, including economic barriers, infrastructure limitations, and safety concerns. Despite these obstacles, hydrogen presents numerous opportunities for future innovation, especially in the context of decarbonizing sectors such as transport, industry, and power generation.

Key Words: Hydrogen energy, renewable hydrogen, fuel cells, electrolysis, hydrogen production, energy transition.

1. INTRODUCTION

Fossil fuels currently meet a significant portion of global energy demand; however, the negative environmental impacts of their combustion, such as greenhouse gas emissions and acid rain cannot be overlooked [1]. As a result, there is a growing global push for an energy transformation, driven by the rapid expansion of renewable energy sources. Hydrogen is emerging as a potential alternative energy carrier, as it produces no local pollution when used in fuel cells—its only byproduct is pure water [2]. Additionally, hydrogen has a high specific energy density, providing three times more energy by mass than gasoline [3]. Furthermore, hydrogen can be locally produced, reducing dependence on foreign energy sources, and it can be derived from various resources, including water, oil, gas, biofuels, and sewage sludge [4]. The abundance of water on Earth further supports hydrogen's potential for sustainable production, particularly through

water electrolysis, which aligns well with renewable energy systems [5]. This process allows for hydrogen to be produced as needed, making it suitable for both distributed and centralised production connected to remote renewable resources [6]. Hydrogen produced from electrolysis is ideal for use with fuel cells, and stationary fuel cell technologies enable the development of distributed power backup systems, stand-alone power plants, and co-generation, offering an alternative to traditional power grids [7]. Hydrogen holds the potential to provide economically viable, efficient, and socially beneficial solutions to address the growing global energy demand, including mitigating climate change [8]. Recent studies emphasise the inevitability of transitioning from traditional energy systems to sustainable alternatives, with hydrogen playing a pivotal role in this shift [7]. As the most abundant element in the universe, hydrogen is primarily found on Earth in water and organic compounds [9]. It is the lightest and simplest element,

consisting of one proton and one electron, and is a colourless, odourless, and flammable gas with an atomic mass of 1.008 [10]. Hydrogen can be produced from a variety of feedstocks, including both fossil fuels and renewable energy resources, using different technologies. A traditional method involves cracking or reforming fossil fuels, which remains a cost-effective approach for industrial hydrogen production [11]. In 2016, approximately 85 million tonnes of hydrogen were produced globally, primarily for applications in fertilizer production, petrochemical refining, and other industrial sectors [12]. However, with the increasing focus on reducing greenhouse gas emissions, renewable energy sources are gaining prominence for producing carbon-emission-free "green hydrogen" [11].

1.1. Hydrogen Properties and Fundamentals

Hydrogen, the most abundant element in the universe, plays a pivotal role in modern energy systems due to its distinct physical and chemical properties. Hydrogen (H_2) is the lightest element, consisting of only one proton and one electron, which makes it a highly reactive and versatile energy carrier [1]. Its atomic mass is approximately 1.008 atomic mass units, which gives it a low energy density by volume but a high energy density by weight. This makes hydrogen an excellent candidate for applications that require high energy outputs, such as fuel cells and aerospace technologies [12].

In its pure form, hydrogen is a colourless, odourless, and highly flammable gas. It has a very low boiling point (-252.87°C), making it a challenge to store and transport at room temperature. Despite its low density, hydrogen can be stored in liquid form at cryogenic temperatures or in high-pressure tanks. One of its most critical properties is its energy content per unit mass. Hydrogen carries about

three times more energy per kilogram than gasoline [3], which makes it an attractive alternative fuel. Hydrogen's potential as an energy carrier is further enhanced by its abundance. While hydrogen is not freely available in its elemental form, it is primarily found in water (H_2O) and organic compounds like hydrocarbons and biomass. Water, which covers approximately 71% of the Earth's surface, offers a sustainable and abundant source for hydrogen production through the process of electrolysis [5]. Electrolysis involves splitting water into hydrogen and oxygen using electricity, and when the electricity is sourced from renewable energy, this process becomes a carbon-neutral method of producing hydrogen.

1.2. Hydrogen's Role in Energy Systems

Hydrogen has the potential to play a transformative role in modern energy systems, particularly in achieving energy security, reducing greenhouse gas emissions, and advancing the transition to sustainable energy. As the global community seeks to address climate change and reduce dependence on fossil fuels, hydrogen presents an opportunity to decarbonise various sectors, including transportation, industry, and power generation [7]. Hydrogen offers a cleaner alternative, as it produces only water vapour when used in fuel cells, without the harmful emissions typically associated with combustion-based energy sources [13]. Hydrogen can serve as a carbon-free fuel for transportation, including Hydrogen Fuel Cell Vehicles (FCVs), which emit zero tailpipe emissions compared to traditional gasoline or diesel vehicles [9]. Additionally, hydrogen is being explored as a solution for decarbonising heavy industries, such as steel production, where it can replace fossil fuels in high-temperature processes [12].

Hydrogen's synergy with renewable energy sources such as wind, solar, and hydropower is particularly significant in the context of

global efforts to decarbonise energy systems. One of the most exciting prospects for hydrogen lies in its ability to store excess energy from intermittent renewable sources. For instance, during periods of low electricity demand or high renewable generation, surplus electricity can be used to produce hydrogen via electrolysis. This hydrogen can then be stored and used later to generate electricity or fuel vehicles when renewable energy generation is low or demand is high [1]. This coupling of hydrogen with renewable energy systems can help stabilize energy grids and improve the resilience of energy infrastructure, particularly in regions with variable renewable energy availability [6].

Furthermore, hydrogen can contribute to energy security by diversifying energy sources and reducing dependence on external suppliers of fossil fuels. As hydrogen can be produced locally from abundant resources like water, countries can reduce their reliance on imported oil and gas, thus enhancing energy independence [5]. In addition, hydrogen can be stored for long durations, which addresses one of the key challenges in energy storage—seasonal variations in demand and supply. It can also be distributed through pipelines and refuelling stations, creating a flexible infrastructure capable of supporting various energy applications, from transport to industry and residential energy needs.

1.3. A Brief History of Hydrogen Energy

The concept of hydrogen as an energy carrier dates back to the early 19th century. In 1800, British scientists William Nicholson and Sir Anthony Carlisle first discovered the process of electrolysis, which involves using electricity to split water into hydrogen and oxygen [1]. This discovery laid the groundwork for hydrogen's potential use as a fuel source. Hydrogen gained significant attention in 1937 when the Hindenburg airship, which relied on hydrogen for buoyancy, tragically caught fire. This event contributed to a longstanding

public perception of hydrogen as a dangerous fuel [12]. However, interest in hydrogen energy was revived during the 1970s oil crisis, which spurred research into alternative fuels. The development of hydrogen fuel cells as, was initially employed by NASA in the 1960s for space missions, gradually transitioned to terrestrial applications in the 1990s and 2000s [8]. As shown in Fig. 1, the hydrogen fuel cell is an electrochemical system combining hydrogen and oxygen to generate energy, with the by-products of water and heat. Over the years, numerous milestones have been reached, further advancing hydrogen as a viable energy option.

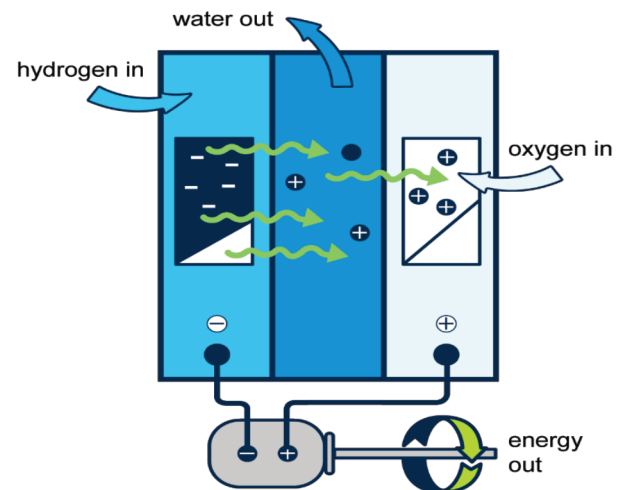


Fig 1. Hydrogen fuel cell

1.4. Hydrogen's Roadmap So Far

The development of hydrogen energy has unfolded over several key phases:

- 1970s-1980s: Research into hydrogen intensified in response to growing fossil fuel dependency, with early tests of hydrogen-powered vehicles and stationary fuel cells [9].
- 1990s-2000s: Progress in hydrogen production technologies and infrastructure development occurred, with companies such as Toyota and Honda

leading efforts to develop Hydrogen Fuel Cell Vehicles (FCVs) [5].

- 2010s: A renewed focus on hydrogen's potential to reduce carbon emissions led to advances in fuel cell technology and the integration of renewable energy sources in hydrogen production [13].
- 2020s and Beyond: Hydrogen has become a critical element in the global transition to clean energy. Countries such as Japan, Germany, and South Korea have launched ambitious hydrogen strategies, investing heavily in hydrogen infrastructure, including production, storage, and distribution systems [7].

2. PRODUCTION OF RENEWABLE HYDROGEN

There are several methods for producing hydrogen for energy purposes:

2.1. Fossil Fuel-Based Hydrogen Production

Hydrogen has traditionally been produced through fossil fuel-based methods, with Steam Methane Reforming (SMR) and coal gasification being the most widely used techniques. These methods, while cost-effective, come with significant environmental concerns, particularly related to carbon emissions, leading to a global push for greener hydrogen production alternatives.

Steam Methane Reforming (SMR) is the most common method of hydrogen production, accounting for approximately 95% of global hydrogen production. This process involves reacting natural gas (primarily methane, CH₄) with steam at high temperatures (700-1000°C) to produce hydrogen gas and carbon monoxide (CO) as a by-product. The reaction can be summarised as:



SMR is a relatively low-cost and mature technology, making it the preferred method in industries such as refining, ammonia production, and chemical manufacturing [16]. However, the process produces a significant amount of carbon dioxide (CO₂), a greenhouse gas contributing to climate change. The carbon emissions from SMR are generally not captured, making it a major source of industrial CO₂ emissions. As a result, SMR has come under increasing scrutiny due to its environmental impact, particularly in the context of global efforts to reduce greenhouse gas emissions [11].

Coal gasification is another method used to produce hydrogen, particularly in regions where coal is abundant and inexpensive. In this process, coal is converted into a gas (syngas) by reacting it with oxygen and steam at high temperatures. The syngas produced primarily consist of hydrogen, carbon monoxide, and carbon dioxide, which can then be further processed to separate the hydrogen. The basic reaction for coal gasification is:



While coal gasification is an established method of hydrogen production, it is less commonly used than SMR due to its higher costs and the increased environmental impact associated with the use of coal [1]. The main environmental concern with coal gasification is the release of CO₂, a potent greenhouse gas. Moreover, the process also produces other harmful pollutants such as sulphur compounds and particulate matter. As with SMR, efforts to mitigate the environmental impact of coal gasification through carbon capture and storage (CCS) technologies are ongoing, but these methods are still costly and not widely adopted.

While both SMR and coal gasification are relatively cost-effective and technologically

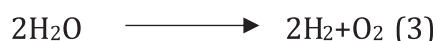
mature, their environmental drawbacks are significant. The primary issue is that these methods rely on fossil fuels, which are non-renewable and contribute to carbon emissions. As such, there is a growing global consensus that fossil fuel-based hydrogen production methods must be phased out in favour of greener, more sustainable alternatives such as green hydrogen, which is produced via electrolysis powered by renewable energy sources [6]. The carbon footprint of SMR and coal gasification makes them increasingly less viable as countries strive to meet climate targets set under international agreements such as the Paris Agreement. Despite their drawbacks, these fossil fuel-based methods remain the dominant means of hydrogen production due to their economic competitiveness. Natural gas, the feedstock for SMR, is relatively abundant and inexpensive, and coal remains a low-cost energy source in some regions. However, as renewable energy technologies continue to develop and become more affordable, the economic advantage of fossil fuel-based hydrogen production is gradually diminishing [12].

There is a clear trend toward reducing reliance on fossil fuel-based hydrogen production methods in favour of cleaner alternatives. Governments, industries, and research institutions are investing heavily in the development of green hydrogen technologies, which produce hydrogen through the electrolysis of water powered by renewable energy sources such as wind, solar, and hydropower [9]. This shift toward green hydrogen aligns with broader goals to decarbonise the energy sector and reduce global carbon emissions. Additionally, carbon capture and storage (CCS) technologies are being explored to mitigate the CO₂ emissions produced by SMR and coal gasification. While CCS could reduce the environmental impact of these methods, it remains expensive and not widely adopted. As such, the future of hydrogen production is likely to be dominated by renewable-powered

electrolysis rather than fossil fuel-based methods, as the world moves toward a more sustainable and low-carbon energy system [6].

2.2. Electrolysis of Water

Electrolysis of water is a highly promising method for producing renewable (green) hydrogen, particularly when powered by renewable energy sources such as wind, solar, and hydropower. This process involves the use of an electric current to split water molecules (H₂O) into their constituent elements: hydrogen (H₂) and oxygen (O₂). The basic reaction for water electrolysis can be summarised as:



When powered by clean, renewable energy sources, electrolysis offers a carbon-neutral process for hydrogen production, making it a key component in the global effort to decarbonise energy systems and combat climate change [6]. This approach avoids the greenhouse gas emissions that are associated with fossil fuel-based hydrogen production methods like Steam Methane Reforming (SMR) or coal gasification [12].

Electrolysis offers a substantial advantage over traditional hydrogen production methods in terms of sustainability. When powered by renewable energy sources such as wind, solar, or hydropower, the hydrogen produced is termed green hydrogen because it is produced with no associated carbon emissions [11]. This is in stark contrast to hydrogen produced via fossil fuel methods, which release carbon dioxide (CO₂) and other pollutants into the atmosphere. Renewable energy sources, such as wind and solar power, have variable outputs, meaning they are intermittent in nature. Electrolysis helps to address this intermittency by acting as an energy storage mechanism. Surplus renewable electricity can be used to generate hydrogen, which can then be

stored and used when renewable power generation is low or when electricity demand is high. This makes electrolysis a key technology in the transition to a sustainable, low-carbon energy system [9]. The ability to produce hydrogen locally also reduces dependence on centralised energy infrastructure and external energy suppliers, further enhancing energy security. Moreover, electrolysis can be used in distributed systems, where hydrogen is produced and consumed locally, making it a suitable technology for decentralised energy production [6].

Recent advancements in electrolysis technology have significantly improved the efficiency, cost-effectiveness, and scalability of hydrogen production. Two of the most promising electrolyser technologies are Solid Oxide Electrolysers (SOECs) and Proton Exchange Membrane (PEM) Electrolysers, both of which have seen notable technological improvements in recent years.

Despite the promising advancements in electrolysis technologies, several challenges remain. The primary limitation is the cost of the electrolysers and the high-energy consumption required for electrolysis. While the cost of renewable electricity has significantly decreased in recent years, the electrolysers themselves remain expensive; particularly those based on PEM and SOEC technologies. Therefore, continued research and development into more cost-effective materials, as well as advancements in manufacturing processes, are critical to making electrolysis a more economically viable solution for large-scale hydrogen production [12]. Another challenge is the need for a robust infrastructure to store, transport, and distribute green hydrogen at scale. While hydrogen can be stored relatively easily, its transportation and distribution require specialised infrastructure that is still in the early stages of development. However, many countries, including Japan, Germany, and South Korea, have made significant investments in hydrogen infrastructure,

signalling that these challenges are being addressed [6].

Looking to the future, the potential for electrolysis-powered green hydrogen is immense. With continued technological advancements, electrolysis could become a key solution in the transition to a carbon-free energy system. The synergy between electrolysis and renewable energy, particularly in regions with abundant wind and solar resources, positions this technology as a major enabler of a sustainable energy future.

2.3. Biomass and Waste-To-Hydrogen

Hydrogen production from biomass and organic waste, including sewage sludge, is gaining increasing attention as a promising and sustainable method to produce hydrogen. This approach involves converting biological materials into hydrogen, which can be utilised as a clean energy carrier. The significant advantage of biomass and waste-to-hydrogen production is that it is considered carbon-neutral, as the carbon dioxide (CO₂) emitted during the carbon absorbed by the organic materials during their growth phase offsets the hydrogen production process. This method is viewed as a potential solution to simultaneously address energy production, waste management, and climate change mitigation [11]. Biomass refers to any organic material that can be used as a source of energy, including wood, agricultural residues, food waste, and other organic matter. Organic waste and sewage sludge are also abundant resources that can be used for hydrogen production through biological or thermochemical processes. The process of converting these materials into hydrogen typically involves gasification, biomass pyrolysis, or biological processes like anaerobic digestion.

Gasification is one of the most widely used methods for biomass-to-hydrogen production. In this process, biomass is heated in a low-oxygen environment, which causes it to

break down into gases like carbon monoxide (CO), methane (CH₄), and hydrogen (H₂). These gases can be further treated to enrich the hydrogen content through additional processes such as steam reforming or water-gas shift reactions [1].

Anaerobic digestion, on the other hand, is a biological process in which organic materials, such as sewage sludge or food waste, are broken down by microorganisms in the absence of oxygen, producing biogas primarily composed of methane. While methane is the primary product, this biogas can be further reformed to produce hydrogen through processes like biogas steam reforming or partial oxidation [12].

The use of biomass and waste materials for hydrogen production offers several important advantages. First and foremost, carbon neutrality is a significant benefit. Biomass is considered carbon-neutral because the CO₂ released during the combustion or conversion process is roughly equivalent to the CO₂ absorbed by the plants during their growth, thus not contributing to the net increase in atmospheric greenhouse gases. This makes biomass a viable option for producing low-carbon hydrogen, particularly in comparison to fossil-fuel-based hydrogen production methods, such as steam methane reforming (SMR), which result in significant carbon emissions [11]. Moreover, biomass and waste-to-hydrogen production can contribute to waste management and circular economy goals. Organic waste, including agricultural residues, food waste, and sewage sludge, often represents a disposal challenge, and using these materials as feedstocks for hydrogen production not only helps mitigate waste accumulation but also turns waste into a valuable energy resource [6]. In particular, sewage sludge, which is typically treated through anaerobic digestion or landfilling, can be converted into hydrogen, reducing environmental contamination and contributing to sustainable energy solutions. Additionally, the use of biomass and

waste as feedstocks offers the potential for localized, distributed hydrogen production, which is important for reducing transportation costs and energy losses. Localised production also enhances energy security, as it reduces dependence on centralised fossil fuel-based energy infrastructure [9].

Recent advancements in biomass and waste-to-hydrogen technologies have led to improvements in efficiency, cost-effectiveness, and scalability. One key development is the optimization of biomass gasification and pyrolysis processes, which enable more efficient conversion of biomass into hydrogen-rich syngas. Innovations in catalysis and reactor design have also enhanced the hydrogen yield from these processes by improving the conversion efficiency and reducing the energy input required for gasification [1]. In addition, biological hydrogen production using microbes has gained attention in recent years. Certain microorganisms, such as green algae and bacteria, have been shown to produce hydrogen through biochemical processes like photobiological or dark fermentation. This biological route for hydrogen production is still in the research and development phase but holds great potential due to its ability to produce hydrogen at ambient temperatures and pressures, reducing the overall energy cost of the process [12].

Despite the promising advantages, biomass and waste-to-hydrogen production face several challenges. One of the primary issues is feedstock variability, as the composition and quality of biomass and organic waste can vary significantly, affecting the efficiency and yield of hydrogen production. Standardizing and optimizing the feedstock selection process, as well as improving the pre-treatment methods (e.g., drying, torrefaction), can help mitigate this challenge [11]. Another significant challenge is the economic feasibility of biomass-to-hydrogen production. The high costs associated with feedstock collection, conversion processes, and infrastructure development

can make this method less competitive compared to other hydrogen production methods. Research into reducing these costs, increasing process efficiency, and scaling up the technology is crucial for making biomass and waste-to-hydrogen production commercially viable [9].

The integration of biomass-to-hydrogen production with existing waste management systems poses a logistical challenge, as infrastructure for waste collection and processing must be adapted to facilitate hydrogen production. However, with the growing demand for renewable energy and sustainable waste solutions, investments in this technology are likely to increase, leading to improvements in both process efficiency and economic viability [6].

2.4. Other Emerging Technologies for Hydrogen Production

As the world seeks more sustainable and efficient methods for hydrogen production, research is advancing in a range of emerging technologies that offer the potential for producing clean hydrogen. Among these innovative approaches are microbial biomass conversion and photo-electrochemical water splitting, both of which have gained significant attention for their sustainability, low environmental impact, and the potential to complement existing hydrogen production methods. While these technologies are still in the research phase or early stages of commercialisation, they offer promising future pathways to meet global energy demands in an environmentally friendly manner.

2.5. Microbial Biomass Conversion for Hydrogen Production

Microbial biomass conversion refers to the biological process in which microorganisms, such as bacteria or algae, are used to convert organic biomass into hydrogen. These

microorganisms can produce hydrogen through a variety of biochemical processes, including dark fermentation and photo-fermentation. The primary advantage of microbial biomass conversion is its ability to operate under mild conditions, ambient temperatures and pressures making it a relatively low-energy process. This characteristic significantly reduces the overall energy input compared to conventional high-temperature and high-pressure methods like steam methane reforming [12].

Dark Fermentation: In dark fermentation, microorganisms break down organic compounds (such as sugars) in the absence of light to produce hydrogen, carbon dioxide, and other by-products. This process has attracted attention for its potential to convert waste materials, such as agricultural and food waste, into hydrogen efficiently [14]. The primary challenge, however, is optimizing the hydrogen yield, as dark fermentation typically produces low concentrations of hydrogen.

Photo-fermentation: This process involves photosynthetic microorganisms, such as purple non-sulfur bacteria, that use light energy to break down organic substrates into hydrogen. Photo-fermentation has the potential to achieve higher hydrogen yields compared to dark fermentation due to the use of light energy, but it is still limited by factors such as the efficiency of light absorption and the low rate of hydrogen production [15].

The main challenges with microbial biomass conversion are low hydrogen production rates, feedstock availability, and the need for specialized cultivation conditions. However, as research progresses, genetically engineered strains of microorganisms and improved bioreactors are expected to overcome these limitations, making microbial biomass conversion a viable method for sustainable hydrogen production in the future [14].

2.6. Photo-electrochemical Water Splitting for Hydrogen Production

Photo-electrochemical (PEC) water splitting is another emerging method for hydrogen production that holds great promise. This process involves using sunlight to drive the electrochemical splitting of water into hydrogen and oxygen, utilizing a photo-electrode made of semiconductor materials. As shown in Fig. 2, PEC water splitting mimics photosynthesis, where sunlight is used as the energy source to produce hydrogen fuel, making it a highly attractive method for producing green hydrogen. The key advantage of PEC over traditional electrolysis is its ability to directly convert sunlight into chemical energy without the need for an external power supply, which can enhance overall system efficiency [16].

PEC technology is still in the research and development phase, with ongoing efforts to improve the efficiency and stability of photo-electrodes. One of the significant challenges with PEC water splitting is improving the performance of semiconductor materials, such as titanium dioxide (TiO_2) and copper-based alloys, which are commonly used as photo-electrodes. These materials need to have high photocatalytic activity and long-term durability to make the technology commercially viable [17]. Research has focused on doping and modifying the surface properties of these materials to enhance their light absorption and improve their overall performance [17].

Another challenge is the Hydrogen Evolution Reaction (HER), where the reaction rate for producing hydrogen can be slow due to poor catalyst performance. Advances in catalyst development, including the use of noble metals like platinum and non-noble metals like nickel, are expected to enhance the efficiency of the PEC system [16].

Both microbial biomass conversion and photo-electrochemical water splitting represent exciting avenues for producing

hydrogen sustainably and cost-effectively. As renewable energy sources, such as wind, solar, and hydropower, continue to grow, these technologies offer the potential for carbon-neutral hydrogen production. Microbial biomass conversion can use organic waste and biomass, addressing waste disposal issues while generating clean hydrogen. Similarly, PEC water splitting can offer a direct link between solar energy and hydrogen production, which could lead to highly efficient systems in the future. The future of these technologies depends on addressing several technical challenges, such as improving reaction efficiency, scalability, and economic feasibility. Continued research into material science, biotechnology, and engineering is expected to unlock the full potential of these methods and make them competitive with other hydrogen production technologies like electrolysis and biomass gasification [14, 16]. As these emerging technologies mature, they may play a crucial role in the global transition to sustainable, clean hydrogen production.

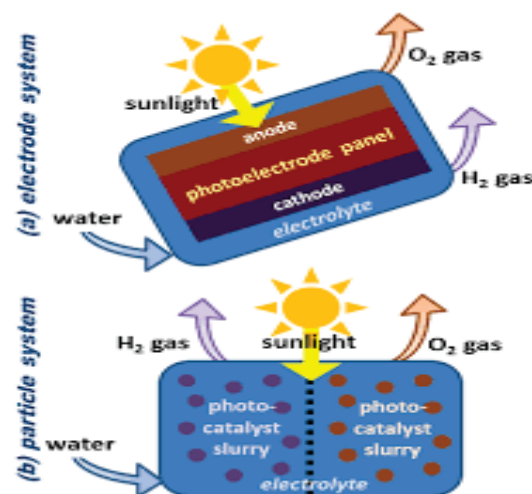


Fig 2. Photo-Electrochemical water splitting

3. NIGERIA'S HYDROGEN ENERGY JOURNEY

Nigeria, as a country with substantial energy potential, has increasingly focused on transitioning to clean energy sources. While fossil fuels, particularly oil and natural gas, have long been the cornerstone of Nigeria's energy sector, there is growing recognition of the need to diversify its energy mix. The adoption of hydrogen as an alternative energy source is a key aspect of Nigeria's long-term energy strategy, aligning with global efforts to reduce greenhouse gas emissions and mitigate the impacts of climate change.

3.1. Nigeria's Energy Landscape and Hydrogen Potential

Nigeria is the largest producer of oil and natural gas in Africa, and the country's energy sector is primarily reliant on fossil fuels. Despite its abundant fossil fuel reserves, Nigeria faces challenges such as power shortages, unreliable electricity supply, and increasing energy demands from its rapidly growing population. Consequently, there is an urgent need for alternative, sustainable energy solutions to meet these demands and support long-term economic growth. Hydrogen energy could be an essential part of Nigeria's energy diversification strategy, particularly when considering the country's vast renewable energy potential, including abundant solar, wind, and hydropower resources [18]. Nigeria's substantial natural gas reserves also provide an opportunity for blue hydrogen production, whereby hydrogen can be produced through steam methane reforming (SMR) with carbon capture and storage (CCS), reducing the overall carbon footprint [19].

3.2. Current Developments and Initiatives

Although Nigeria's hydrogen energy sector is in the early stages of development, several

initiatives signal growing interest in exploring hydrogen's potential. The Nigerian government, in collaboration with international partners and institutions, is beginning to outline a roadmap for hydrogen energy adoption. In 2021, the Nigerian National Petroleum Corporation (NNPC) and other stakeholders expressed interest in exploring hydrogen production as part of the country's broader efforts to diversify its energy mix and meet net-zero emissions targets [20].

Notably, Nigeria has also expressed interest in green hydrogen production, particularly through electrolysis powered by renewable energy sources. With its vast solar energy potential, particularly in the northern regions, Nigeria is well positioned to produce green hydrogen, which could support both domestic needs and international export markets. Additionally, several international energy companies have shown interest in collaborating with Nigeria to develop hydrogen technologies and infrastructure, enhancing the country's capacity to harness this clean energy source [18].

3.3. Challenges in Hydrogen Energy Adoption

Despite the significant potential, there are several challenges to the widespread adoption of hydrogen energy in Nigeria. One of the key barriers is the high cost of hydrogen production, particularly green hydrogen, which requires significant investment in renewable energy infrastructure and electrolyzers [21]. The country's current energy infrastructure, predominantly based on fossil fuels, would also need substantial upgrading to accommodate the storage, distribution, and use of hydrogen.

Moreover, there is a need for comprehensive regulatory frameworks and policy support to facilitate the development of a hydrogen economy. The government would need to establish incentives for private investment in hydrogen technologies, as well as implement policies to

encourage research and development in the sector [19].

3.4. Hydrogen in Nigeria's Industrial Sector

In addition to its potential role in power generation and transportation, hydrogen could also play a vital role in Nigeria's industrial sector, particularly in refining, steel production, and ammonia production. The use of hydrogen in industrial processes could help Nigeria reduce its dependence on fossil fuels for these energy-intensive sectors, aligning with global efforts to decarbonise heavy industries. As Nigeria continues to build its hydrogen infrastructure, hydrogen could serve as a clean fuel for industrial applications, contributing to the country's overall decarbonisation goals [20].

3.5. The Future of Hydrogen Energy in Nigeria

Looking forward, Nigeria's hydrogen energy journey has the potential to transform its energy sector. The country is uniquely positioned to leverage its renewable energy resources, existing gas infrastructure, and growing interest in sustainable energy solutions to develop a robust hydrogen economy. However, overcoming the technological, financial, and policy barriers will require significant investment, international collaboration, and long-term strategic planning.

As hydrogen energy technologies mature and become more cost-competitive, Nigeria could emerge as a regional leader in hydrogen production, not only meeting domestic energy needs but also serving as a key exporter of clean energy to international markets. With the right policies and investments, hydrogen could become a cornerstone of Nigeria's transition to a sustainable and diversified energy future [21].

4. POTENTIALS OF HYDROGEN ENERGY

4.1. Hydrogen in Industry: A Crucial Feedstock for Manufacturing

Hydrogen plays a pivotal role in many industrial processes, particularly in sectors such as refining, ammonia production, steel manufacturing, and food processing. In oil refining, hydrogen is used in hydrocracking and desulfurization to break down heavy crude oil into more valuable fuels and to remove sulphur compounds from refined fuels, ensuring compliance with environmental regulations [12]. In ammonia production, hydrogen is a key component in the Haber-Bosch process, which synthesizes ammonia from nitrogen and hydrogen for use in fertilizers, which are essential for global food production [11].

In steel manufacturing, hydrogen can replace coke as a reducing agent in the direct reduction of iron (DRI) process, significantly reducing the carbon emissions associated with traditional steelmaking methods [9]. Hydrogen's potential to replace carbon-intensive processes with clean alternatives is crucial to achieving the decarbonisation goals set by many industries. Additionally, in food processing, hydrogen is used to produce hydrogenated oils, which are common in food manufacturing for producing products such as margarine and shortening [13]. Hydrogen's application as a feedstock in these industries is essential for meeting global sustainability goals, particularly in reducing carbon emissions and environmental impacts in heavy industries, which are traditionally major contributors to air pollution and greenhouse gas emissions.

4.2. Hydrogen for Clean Transportation: Fuel Cell Vehicles and Infrastructure

One of the most promising applications of hydrogen is in the transportation sector, where hydrogen fuel cell vehicles (FCVs) offer an alternative to conventional internal combustion

engine (ICE) vehicles and battery electric vehicles (BEVs). Hydrogen-powered vehicles are particularly advantageous because they offer longer driving ranges compared to BEVs, which are limited by battery capacity. Additionally, FCVs can be refuelled in minutes, unlike BEVs, which typically require a longer charging time [16].

The current hydrogen vehicle market is expanding, with automakers such as Toyota, Honda, and Hyundai already producing hydrogen-powered cars like the Toyota Mirai, Honda Clarity, and Hyundai Nexo. The success of these vehicles depends heavily on the development of hydrogen refuelling infrastructure, which remains limited compared to charging stations for BEVs. However, there is growing investment in hydrogen refuelling stations in key regions such as California, Japan, and Germany, where government incentives and support are helping to create the necessary infrastructure for a hydrogen economy [16].

Beyond passenger cars, hydrogen has potential applications in larger forms of transportation, such as fuel-cell buses, trucks, and even ships. Fuel cell buses have already been deployed in several countries, and the next steps include expanding their use in public transportation systems worldwide. Similarly, hydrogen-powered trucks are being developed to offer longer-range, zero-emission alternatives to diesel trucks, which are responsible for significant air pollution and greenhouse gas emissions [11, 22].

Hydrogen for maritime transport is also gaining attention, with several companies and research institutions working on hydrogen-powered ships to decarbonize the shipping industry, which is a major contributor to global carbon emissions. While these technologies are still in the early stages of development, they represent a promising pathway for reducing emissions from both land and sea transport.

5. CHALLENGES AND BARRIERS TO HYDROGEN ADOPTION

The transition to a hydrogen economy holds significant potential for decarbonizing various sectors, but several challenges hinder its widespread adoption. These challenges span economic, technological, policy, regulatory, and safety concerns, all of which need to be addressed to facilitate the scaling up of hydrogen technologies.

5.1. Economic and Financial Barriers

The high costs associated with hydrogen production, especially from renewable sources, remain a major barrier to widespread hydrogen adoption. Currently, green hydrogen, produced via electrolysis powered by renewable energy sources like wind, solar, or hydropower, is significantly more expensive than hydrogen produced from fossil fuels using methods like steam methane reforming (SMR) or coal gasification [International Energy Agency [9]. The capital costs of building electrolysis plants and renewable energy infrastructure, as well as the costs of electricity used in electrolysis, make green hydrogen economically uncompetitive with fossil fuel-based hydrogen.

In contrast, blue hydrogen, produced from natural gas with carbon capture and storage (CCS), is more cost-competitive but still relies on fossil fuels and does not fully eliminate carbon emissions [23]. As of now, green hydrogen can cost as much as three to five times more than grey hydrogen (produced from natural gas without CCS) [24]. Although the costs of renewable hydrogen are expected to decrease with advances in technology and the scaling up of production, the economic viability of hydrogen remains a challenge. Policy incentives, including carbon pricing, subsidies for renewable energy production, and research and development funding, are crucial to bridging the price gap and making green hydrogen more competitive.

5.2. Technological Barriers

Technological challenges in hydrogen production, storage, and fuel cell technology are significant barriers to hydrogen adoption. In hydrogen production, although electrolysis holds promise, it is still energy-intensive and requires improvements in the efficiency of electrolyzers. Currently, most electrolyzers are expensive and operate at low-efficiency levels, with energy losses occurring during hydrogen production. Solid oxide electrolyzers and proton exchange membrane (PEM) electrolyzers have made significant advances, but further research is needed to improve their efficiency, cost-effectiveness, and durability [22].

In hydrogen storage, the challenges are related to the low volumetric energy density of hydrogen, which requires high-pressure storage or cryogenic storage technologies to maintain a viable amount of energy. Compressed hydrogen is stored in high-pressure tanks, which are expensive and require complex safety protocols. Liquid hydrogen offers higher energy density but necessitates cryogenic temperatures to remain in liquid form, posing further cost and energy challenges. Solid-state storage is also an area of active research, but finding suitable materials that can efficiently absorb and release hydrogen remains a challenge [25]. Fuel cell technology, while offering high efficiency and zero emissions, faces challenges related to the high costs of platinum-based catalysts, which are required for hydrogen oxidation reactions. The scarcity of platinum and its high cost makes fuel cell systems expensive. Significant progress is being made in exploring alternative catalysts and catalyst designs, but these technologies still require substantial research before they can be commercially viable [8].

5.3. Policy, Regulation, and Infrastructure Challenges

The lack of regulatory frameworks and the slow pace of infrastructure development are additional barriers to hydrogen adoption. In many regions, there is no clear regulatory framework to govern the production, storage, and transportation of hydrogen, leading to uncertainty and reluctance among investors and industries. Policy incentives are essential to overcoming these barriers, with governments needing to establish subsidies, carbon pricing, and research and development programs to stimulate hydrogen technologies. Without government support, the cost of developing hydrogen infrastructure—such as refuelling stations, storage facilities, and distribution networks—will remain prohibitively high, limiting hydrogen's role in the energy transition [19].

A robust global hydrogen infrastructure is necessary for hydrogen to become a mainstream energy carrier. Pipelines, shipping, and tankers are all part of the complex infrastructure needed to transport hydrogen across regions and continents, but the development of such infrastructure is costly and faces regulatory challenges related to safety standards and public perception. The cost of building pipelines and establishing refuelling stations for vehicles is one of the key barriers to scaling up hydrogen adoption, especially in regions that lack the necessary infrastructure [7].

International collaboration and the development of global standards for hydrogen production, storage, and transport will be essential for creating a hydrogen economy that can meet global energy needs and reduce carbon emissions. In this context, government support through subsidies, funding for infrastructure projects, and the establishment of clear regulatory frameworks is critical.

5.4. Safety and Public Perception

The safety concerns surrounding hydrogen's flammability and the perceived risks associated with its storage and transportation are important barriers to public acceptance. Hydrogen is a highly flammable gas with a wide flammability range, and accidents such as the Hindenburg disaster have fuelled public fear of hydrogen. While modern hydrogen technologies are much safer due to advances in storage materials and handling procedures, public perception often remains skeptical about hydrogen's safety compared to other energy carriers, such as electricity or natural gas [24].

To address these concerns, public education is vital to increase awareness about hydrogen's safety features and its potential benefits in reducing carbon emissions. Standards and codes of practice for hydrogen storage and transportation are also important in ensuring the safety of hydrogen infrastructure. Governments and industry stakeholders must work together to develop communication strategies that clearly explain the safety measures in place and promote the advantages of hydrogen as a clean energy source.

6. CONCLUSION

Hydrogen energy holds promise as a key component of a sustainable and low-carbon future. Its versatility, clean energy profile, and potential to enable energy storage make it an attractive option for a greener world. However, economic and technological barriers must be addressed to realize its full potential. Continued research, investment, and public awareness are crucial for the successful integration of hydrogen into the global energy mix. The next decade will be pivotal, as the world navigates the path towards a cleaner energy system and hydrogen plays an increasingly central role in this transition. By balancing its strengths and addressing its challenges, hydrogen energy could be a cornerstone of

the global clean energy future, driving us towards sustainability and energy security.

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DEVELOPMENT AND TESTING OF PYROLYSIS MACHINE FOR SUSTAINABLE WASTE MANAGEMENT

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Abstract: This study explores sustainable methods for managing waste biomass through the creation of a pyrolyzer model aimed at converting waste biomass into fuel. The apparatus operates as a batch reactor with a fixed bed design, specifically engineered to extract pyrolysis oil and gas, which can be further refined into usable fuel. The pyrolyzer comprises a reactor with a volume of 0.0254 m³ and a copper spiral condenser that is 2 m long. The research focused exclusively on High-Density Polyethylene (HDPE) as a case study, sourced locally. The HDPE was washed, dried, and cut into pieces measuring 1 to 3 cm. During the testing phase, 100 g of HDPE was placed into the pyrolysis reactor at an ambient temperature of 25 °C and subsequently heated. The plastics melted at 110 °C and vaporized at 700 °C. The resulting hot vapor was circulated through a copper coil for condensation, yielding a liquid product known as pyrolysis oil and gas. The results indicate that the pyrolysis of HDPE produces a heavier liquid fraction with a yield of 60 wt.%. Combustion tests of the produced gas reveal that the pyrolysis of HDPE generates products suitable for use as combustible gas and liquid fuel. Consequently, pyrolysis presents a viable alternative for the recycling of various types of plastic waste.

Key Words: Pyrolysis, Plastic, Oil, Design, Heating rate, Gas

1. INTRODUCTION

Plastic waste is typically produced by human activities and industrial processes as long as human life continues. This is due to the necessity for raw materials and finished products that humans rely on, which inevitably results in waste generation. When not properly managed, plastic waste takes up space, creates unsanitary conditions, and fosters disease-causing organisms, ultimately threatening human health [1].

Global plastic production has shown a persistent upward trend, even though recycling rates remain alarmingly low, with only approximately 15% of the 400 million tons of plastic generated annually being recycled [2]. Over the last thirty years, the increase in global plastic production and consumption has significantly outstripped the rates of

recycling, suggesting that a larger quantity of plastic waste is entering the environment [2]. Projections indicate that by 2050, global plastic production may triple, potentially accounting for one-fifth of the total oil consumption worldwide [3]. The conversion of waste plastics into a combustible liquid fuel can be achieved through the pyrolysis process [4]. The University of Oxford projects that plastic waste is anticipated to rise to approximately 12 billion tons by the year 2050 [5].

Nigeria produces more than 32 million tons of solid waste annually, ranking among the highest in Africa [6]. Of this total, plastic waste constitutes approximately 2.5 million tons [7]. The attributes of plastic, including its affordability, lightweight nature, and resistance to chemicals and corrosion, have led to its increased preference for

packaging and storage compared to alternative materials [1, 7]. Consequently, the proportion of plastic in global household solid waste and its environmental repercussions are on the rise. In response to these challenges, both developed and developing nations have established and are enhancing their systems for the disposal, collection, and recycling of plastic waste. However, in Nigeria, which has an estimated population of around 186 million, there is a notable lack of data regarding the presence of plastic products in urban areas and the methods employed for their disposal, collection, and recycling [7].

Numerous techniques exist for waste disposal and management; however, some methods are notably more sustainable, facilitating volume reduction while simultaneously generating energy and recovering valuable raw materials that are advantageous to human society. In Nigeria, the prevalent systems for managing plastic waste encompass landfill disposal, incineration, and open burning [8]. It is important to note that both incineration and open burning primarily serve to diminish the volume of plastic waste, yet they fail to produce energy and contribute to environmental pollution through the release of greenhouse gases.

One viable method for transforming plastic waste into fuel is pyrolysis. This process encompasses a series of intricate chemical and thermal reactions that facilitate the depolymerization of organic materials in an oxygen-free environment [2]. Specifically, pyrolysis involves the thermal degradation of long-chain polymers, resulting in the conversion of plastics into solid, liquid, or gaseous fuels. The byproducts of this process include high-calorific gas, premium-quality oils, and carbonized char. Under moderate conditions, pyrolysis can yield up to 80 weight percent of these products, operating at temperatures ranging from 300 to 900°C [9].

[10] indicated that the gases generated during the pyrolysis of organic substances encompass carbon monoxide, carbon dioxide, water vapor, hydrogen, methane, ethane, ethene, propane, propene, butane, butene, among others. The temperature and heating rate is crucial, as these factors significantly affect the outcomes of the pyrolysis process, allowing to produce specific solid, liquid, and gaseous products. [11] have identified the pyrolysis of waste plastics as a particularly effective method for energy recovery, highlighting that waste plastics serve as a valuable source of chemicals, gases, and liquid fuels.

Plastics are mainly divided into two categories: thermoplastics and thermosetting polymers. Thermoplastics, like polyethylene and polystyrene, can be repeatedly melted and reshaped when heated, making them recyclable. In contrast, thermosetting plastics, such as epoxy resin and phenol formaldehyde, can only be shaped once and cannot be remelted. Common plastic types include Polyethylene Terephthalate (PET), High-Density Polyethylene (HDPE), Polyvinyl Chloride (PVC), Low-Density Polyethylene (LDPE), Polypropylene (PP), and Polystyrene (PS) [12].

The processes of pyrolysis and plastic waste management are increasingly recognized as integral components of sustainable waste management strategies. [13] conducted a study on the mechanical recycling of solid plastic waste at a small scale. [14] examined the thermochemical and kinetic aspects of plastic waste combustion, while [15] detailed various methods for the thermochemical conversion of plastic waste. According to [16], pyrolysis of plastic waste can yield alternative fuels. [17] argued that pyrolysis is a viable recycling option within sustainable frameworks.

Pyrolysis effectively transforms plastic waste into valuable by-products like fuel and carbon black, reducing landfill reliance [18]. Designing a plastic pyrolysis machine is crucial for minimizing waste and promoting a circular economy. This study aims to create a pyrolysis reactor that recycles plastic waste into fuel, featuring a control panel to manage temperature and accommodate various feedstocks while ensuring efficient heat transfer and reduced retention times.

2. MATERIALS AND METHODS

This research was conducted at the Laboratory of the National Centre for Petroleum Research and Development, a division of the Energy Commission of Nigeria. The methodology followed standard engineering practices, starting with the conceptual phase, moving on to the selection of an optimal device, and concluding with the design and engineering drawings.

2.1 Materials:

The plastic materials utilized in this research were High Density Polyethylene (HDPE), sourced from the vicinity of the organization. This material was selected due to its prevalence and ease of access within the study area. The collection process involved gathering the plastics, followed by sorting and meticulously washing them by hand with distilled water. Subsequently, the materials were sun-dried and then cut into chips using scissors. The dimensions of the pyrolysis feedstock were standardized to a range of 1 to 3 cm.

2.2. Design of the pyrolysis unit:

In the context of this research, a pyrolysis unit has been conceptualized and modeled using the 3D CAD software 'SolidWorks' and subsequently constructed. This unit comprises four primary components: a pyrolysis reactor, a

heating chamber, a condensation and product recovery system, and a supporting structure. The design of these components was informed by the thermal decomposition characteristics of plastics and the principles that regulate the functioning of pyrolysis reactors. Detailed drawings and descriptions of each component of the pyrolysis machine are presented in Table 2 of the Appendix.

3.0 MACHINE DESCRIPTION

The process illustrated in Figure 1 involves the collection, washing, and drying of plastic feed material. Subsequently, this material was reduced in size of 1 to 3 cm through scissors cutting. The processed feed was then weighed and introduced into a manually secured fixed bed reactor. Following this, char was separated using a cyclone, while the gases were quenched to facilitate the condensation into liquid bio-oil, with the remaining products being gas and bio-char. High-temperature adjustable gaskets were employed to ensure the integrity of the flange joints of the reactor and teflon in the discharge pipe fittings and condenser inlet and outlet pipe fittings. The condenser was filled with water and cooled using a chiller unit. The heating of the reactor was achieved via an electric band that is affixed to a mild steel pipe, into which the reactor is inserted, as shown in Figure 2. Carbon dioxide gas was introduced into the reactor through a pipe connected to its upper section. The assembly was disassembled once the rig had cooled sufficiently for safe handling. The biochar collected from the reactor bed was then weighed.

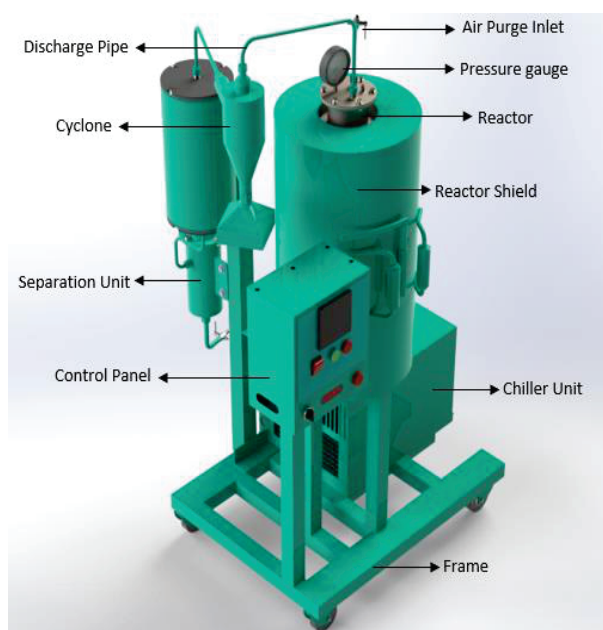


Fig. 1. Components labelling of as-built drawing of the pyrolysis machine

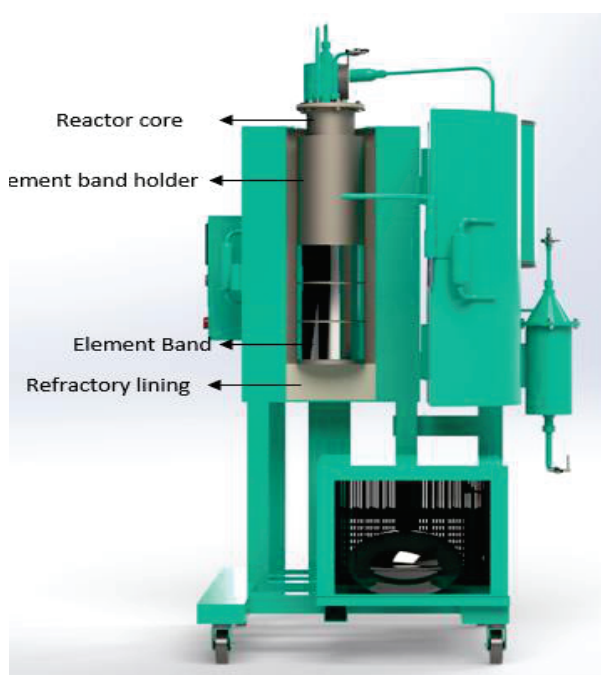


Fig. 2. Components labelling of as-built drawing of the open reactor shield

4. TESTING AND ANALYSIS

Performance evaluations were conducted utilizing high-density polyethylene (HDPE) within the pyrolysis system, as illustrated in Plate 1. The primary objective of these

evaluations was to thoroughly assess the functionality and efficiency of the designed and constructed pyrolyzer. The experiments specifically involved the pyrolysis of 100 g of HDPE plastic material, allowing for a controlled analysis of the process.

In the pyrolysis reactor, the plastics were introduced at an initial ambient temperature of 25 °C. The system was then gradually heated to the melting point of HDPE, which was approximately 110 °C. Once the material reached this temperature, it began to melt and subsequently vaporize at elevated temperatures ranging from 500 to 700 °C. This temperature range was critical, as it facilitates the breakdown of the polymer chains in HDPE, leading to the formation of various gaseous products. During the pyrolysis process, the generated steam and vapors circulate through a copper pipe, which serves as a conduit for the hot gases. Upon completing a full cycle, the condensable fraction of the hot vapors from the reactor is collected and allowed to cool, resulting in the condensation of these vapors into a liquid form. This resultant liquid is referred to as pyrolysis oil, which is depicted in Plate 2. Pyrolysis oil is a valuable product, as it can be further processed or utilized as a fuel source.

Following the production of pyrolysis oil, a straightforward combustion test was performed on the gases generated during the pyrolysis process, as shown in Plate 3. This test aimed to evaluate the combustibility of the gaseous byproducts, providing insights into their potential applications as alternative fuels.

The fixed bed pyrolysis of HDPE demonstrated a maximum oil yield of 60 weight percent when processing HDPE feed particles sized between 1 and 3 cm at a reactor bed temperature of 700 °C. This finding indicates that the pyrolysis process is highly

efficient in converting HDPE into valuable liquid products. Furthermore, it was observed that as the reactor bed temperature increases, there is a corresponding decrease in the weight percentage of char production, while the production of gaseous byproducts rises. This trend highlights the importance of temperature control in optimizing the pyrolysis process, as higher temperatures favor the generation of gases and liquids over solid residues. Overall, the results of these performance evaluations underscore the potential of pyrolysis as a viable method for the conversion of HDPE waste into useful energy resources.



Plate 1. The fabricated pyrolysis machine



Plate 2. The produced pyrolysis oil



Plate 3. Test for the combustibility of the produced gas

4.1 Properties of Pyrolysis Oil obtained

The pyrolysis oil derived from the HDPE sample underwent testing at the Laboratory of the National Petroleum Research and Development of the Energy Commission of Nigeria. The results of these tests are presented in Table 1.

Table 1: Properties of Pyrolysis Oil

Character-istics	Test Method	HDPE sam-ple
Density (@25°C, gm ³)	ASTM D1298	878.5
Kinematic Viscosity (@40°C, cSt)	ASTM D445	2.54

5. CONCLUSION

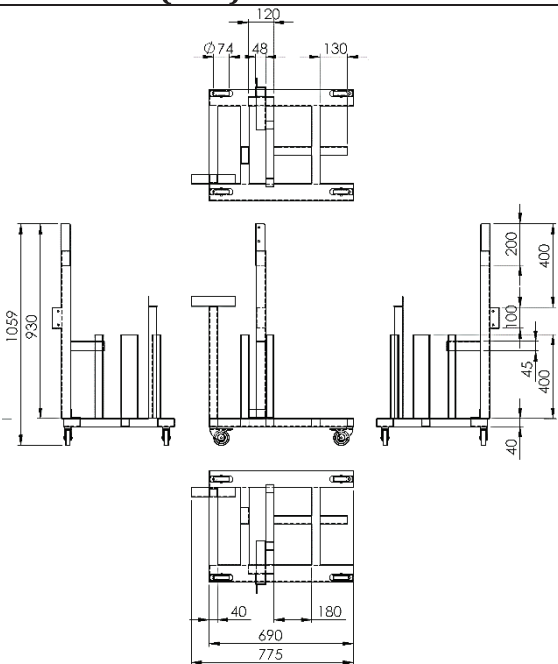
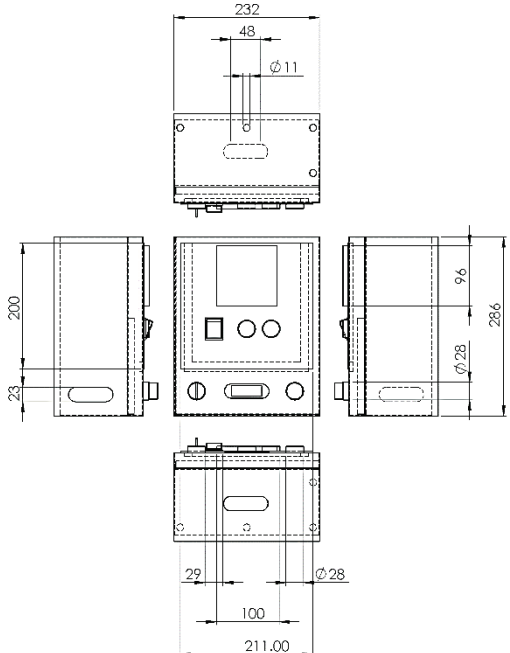
This study aimed to develop a thermochemical recycling system that employs pyrolysis to convert plastic waste into alternative fuels. A batch pyrolyzer was designed and built for this purpose. The results show that certain thermoplastics can be effectively converted into petrochemical products. Notably, a decrease in particle size is associated with an increase in oil yield, with the highest yield of 60 wt.% obtained from the pyrolysis of HDPE at a particle size between 1 to 3 cm. Combustion tests of the produced oil demonstrate that the pyrolysis of HDPE generates products that can be used as combustible gas and liquid fuel. In summary, pyrolysis offers a promising alternative for recycling types of plastic waste.

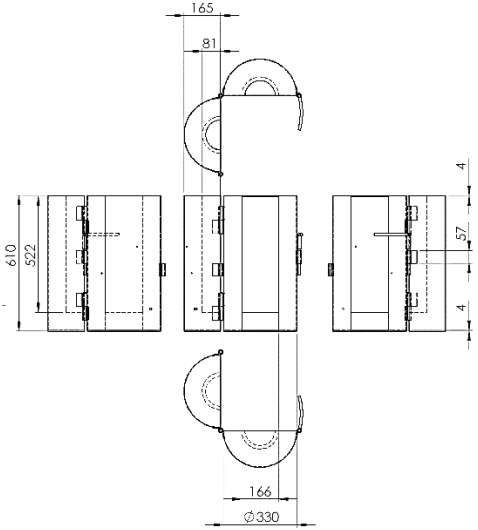
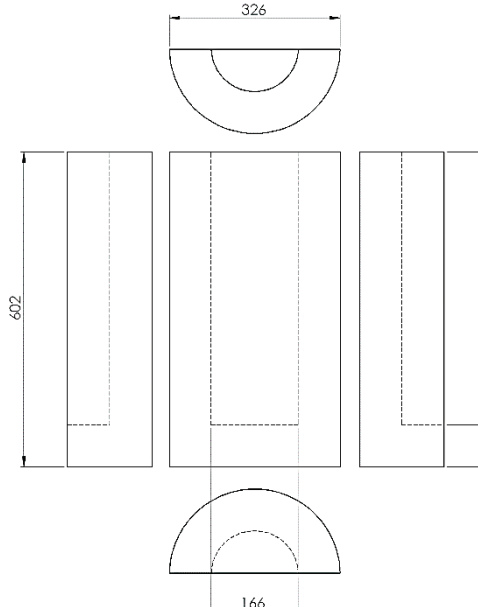
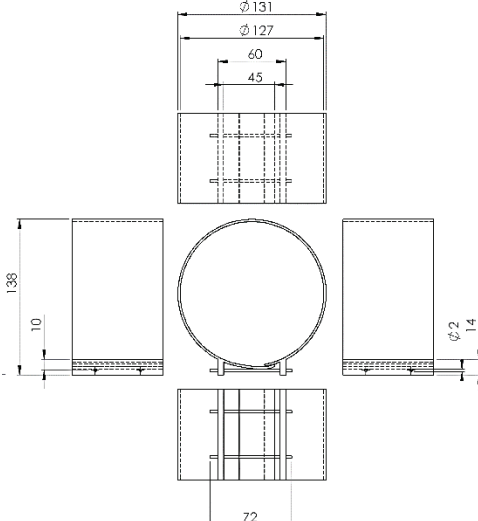
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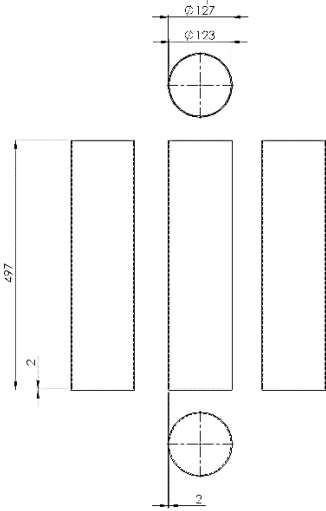
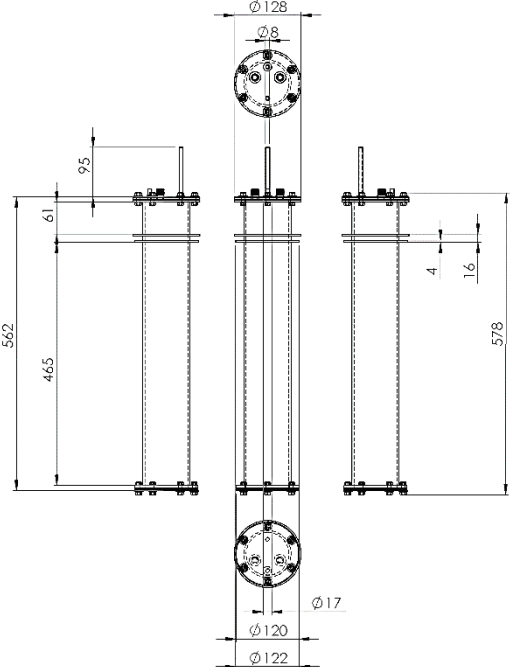
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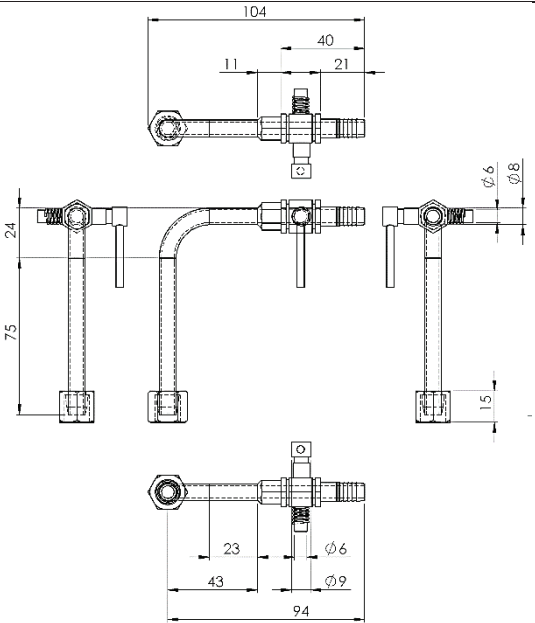
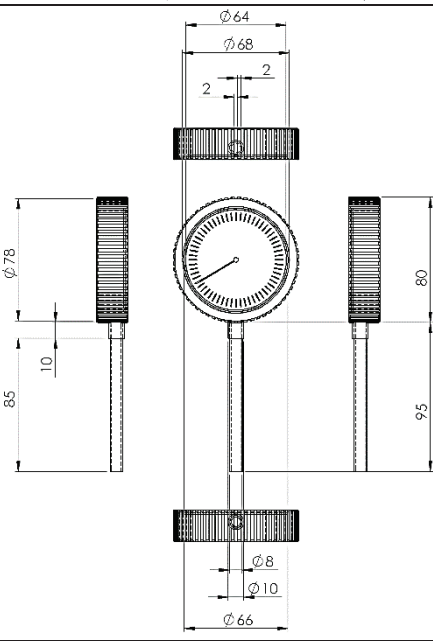
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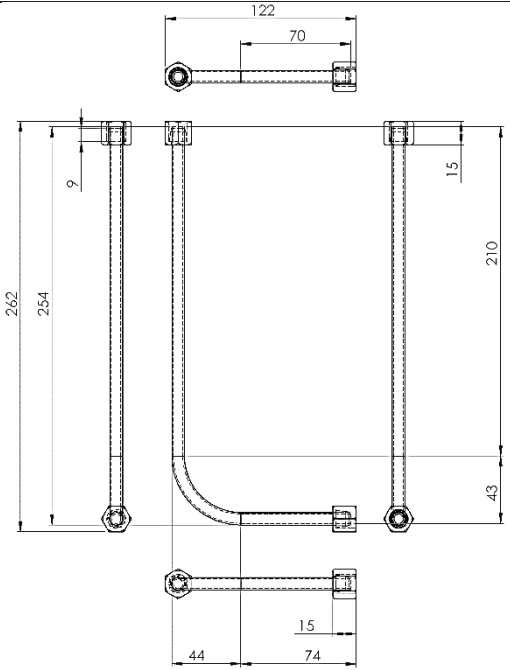
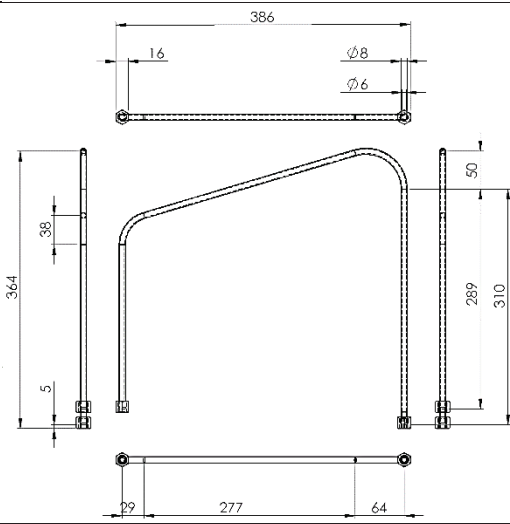
Table 2: Detailed drawing and description of each component of the pyrolysis machine

S/N	ITEM DESCRIPTION	DRAWING (mm)
1	Main Frame: This was constructed from 4 mm carbon steel square pipe. The frame was designed in such a way as to accommodate all the units.	 Technical drawing of the Main Frame showing front, side, and top views with dimensions. The front view shows a width of 775 mm and a height of 1059 mm. The side view shows a depth of 400 mm. The top view shows a width of 690 mm and a depth of 180 mm. Other dimensions include 120, 130, 48, 74, 40, 100, 45, 200, and 400.
2	Control Panel Casing: This was constructed from a 1.5 mm mild steel plate. The plate was shaped as a cuboid with openings to accommodate gas and heater band temperatures display, Power ON /OFF and Condenser ON/OFF indicator lights and switches.	 Technical drawing of the Control Panel Casing showing front, side, and top views with dimensions. The front view shows a width of 211.00 mm and a height of 286 mm. The side view shows a depth of 200 mm. The top view shows a width of 232 mm and a height of 48 mm. Other dimensions include 23, 29, 100, 28, 96, 11, and 28.

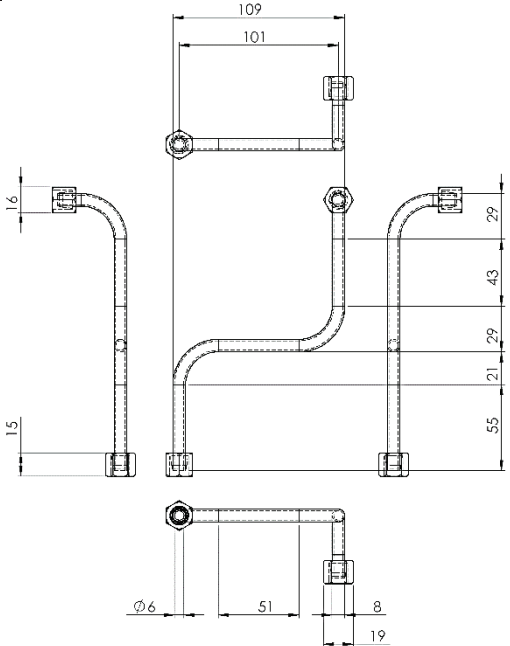
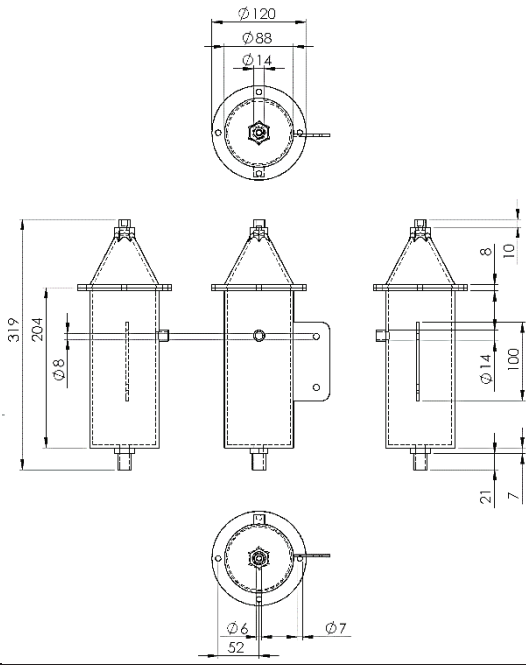
3	Reactor Shield: Is a most important component in fixed bed pyrolysis reactor and is a split type. The reactor shield was made of cylindrical shaped consisting of 4 mm thick mild steel sheet while the lining protector sheet inside was made of 2 mm thick mild sheet. Moreover, the hollow portion was filled with insulating material.	
4	Refractory Lining: Is the protective layer of insulation on the internal surface. The whole body is encased in a metal shell. The lining is made of the composition of the materials; 40% Kaolin, 10% Feldspar, 30% Sawdust, 10% Clay and 10% Silica.	
5	Element Band Heater: 3 bands of 2500 W each wrapped on the outside of mild steel tube heating it. The steel will transfer the heat to the reactor to heat the plastics.	

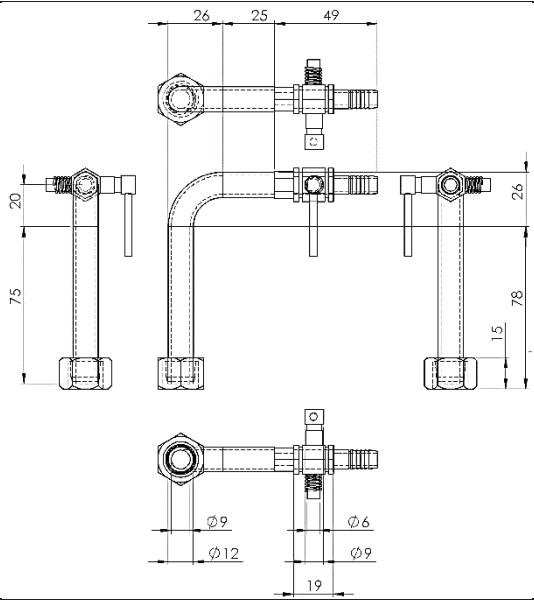
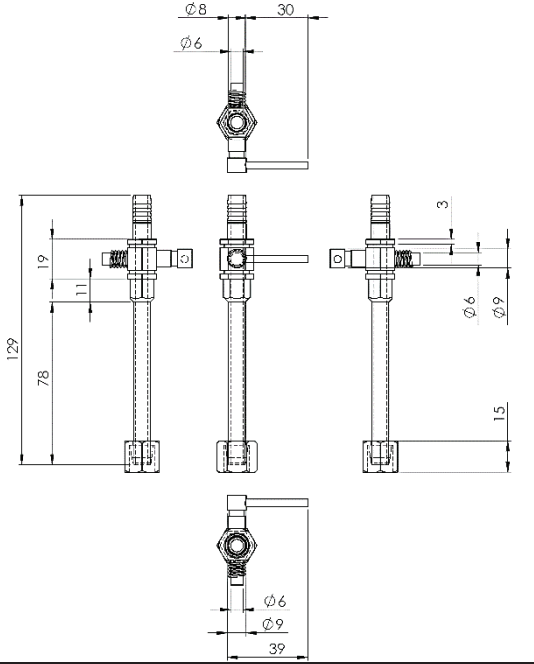
6	Element Band Holder: This is a 2 mm mild steel tube with one end open and the other end closed, on which the band heaters were wrapped. The steel will transfer the heat to the reactor.	
5	Reactor: This was constructed from a stainless-steel pipe and was welded to four carbon steel metal plate flanges of 3 mm thickness. Two were welded at both ends of the reactor and the other two plate flanges were welded at some distance from the top plate flange as shown in the diagram. The reactor has two blind flanges, at the top and bottom of the reactor. It was designed to be opened and closed for loading and off-loading of the reactor with the plastic waste, and also for maintenance of the reactor to be carried out. The blind flanges were constructed from a carbon steel metal plate. Then, the plate was drilled to accommodate the union male fittings, pressure gauge pipe, and temperature sensor hole. The blind flange was designed with 6 holes drilled into it to accommodate six pairs of bolts and nuts to fasten the blind flange to the reactor.	

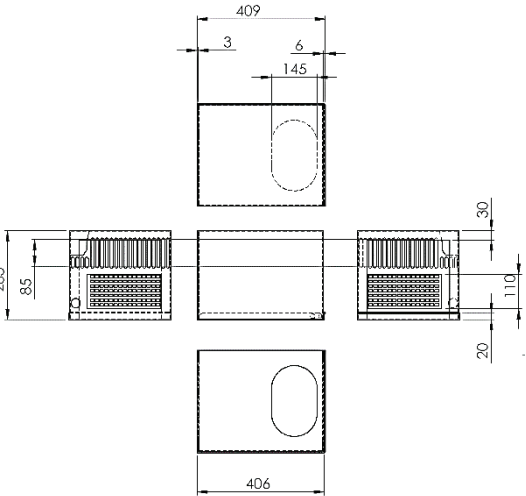
6	Top Vent: This is screwed to the top blind flange through the union male fitting for venting out gases and for the intake of CO₂ for purging out O₂. It was constructed using ball valve type welded to an 8 mm diameter stainless steel pipe.	 Technical drawing of the Top Vent assembly. The drawing includes three views: a top view, a side view, and a front view. The top view shows a horizontal pipe with a ball valve in the center, with dimensions 104, 40, 11, and 21. The side view shows the vertical height of the assembly with dimensions 24, 75, and 15. The front view shows the horizontal distance from the center to the ends with dimensions 23, 43, 94, and diameters $\phi 6$ and $\phi 9$.
7	Pressure Gauge: This is screwed to an 8 mm diameter stainless steel pipe welded to the top blind flange, to measure pressure inside the reactor.	 Technical drawing of the Pressure Gauge assembly. The drawing shows a front view of the gauge mounted on a vertical pipe. The gauge has a circular face with a needle. Dimensions include diameters $\phi 64$, $\phi 68$, $\phi 78$, $\phi 8$, $\phi 10$, and $\phi 66$, and heights 2, 10, 80, and 95.

8	Discharge Pipe to Cyclone: This is an 8 mm diameter stainless steel pipe, screwed to the top blind flange through the union male fitting for discharging of fluid produced from the reactor to cyclone.	
9	Discharge Pipe to Condenser: This is an 8 mm diameter stainless steel pipe, screwed to the top blind flange through the union male fitting for discharging of fluid produced from the reactor to the condenser.	

10	Cyclone: This was constructed from a stainless-steel pipe and plate. It is a short vertical, cylindrical vessel with a conical base. The upper part of the vessel is welded with a pipe as a tangential inlet. The top of the vessel is welded with a short pipe for the discharge of clean gases, and the bottom of the conical base is screwed to a pyramid cuboidal base for the collection of the solid particles.	Technical drawing of a cyclone separator showing three views: front, side, and top. Dimensions include diameters (φ 32.00, φ 88.00, φ 14.00, φ 82.00, φ 32.00) and heights (14.00, 17.15, 44.00, 106.00, 91.63, 33.00, 144.25, 135.76, 10.00).
11	Condenser: This was constructed from a stainless-steel pipe and plate. The pipe was wrapped with a copper pipe coil as an evaporator which was also wrapped with tape and a metal plate. And, the pipe was welded to two stainless steel metal plate flanges of 2 mm thickness. The condenser has two blind flanges, at the top and bottom of the condenser which was sealed with fabric material at their surfaces. It was designed to be opened and closed for loading and off-loading of the condenser with the water, and also for maintenance of the condenser to be carried out. The blind flanges were constructed from a stainless-steel metal plate and were drilled to accommodate the union male fittings. The blind flange was designed with four holes drilled on it to accommodate four pairs of bolts and nuts to fasten the blind flange to the condenser.	Technical drawing of a condenser showing three views: front, side, and top. Dimensions include diameters (φ 166, φ 6, φ 8, φ 12, φ 14) and heights (368.00, 332, 7, 2, 4, 3).

12	Discharge Pipe to Separator: This is an 8 mm diameter stainless steel pipe, screwed to the bottom blind flange of the condenser through the union male fitting for discharging fluid produced from the condenser to the separator.	
13	Separator: This was constructed from a stainless-steel pipe and plate. It is a short vertical, cylindrical vessel with a conical top. The two parts were connected using a plate flange welded to each part with four pairs of bolts and nuts to fasten them together and for easy maintenance. The top of the vessel is welded to a union male fitting and screwed to a short pipe welded with a ball valve for the discharge of gases, and the bottom of the cylindrical base was welded to a union male fitting and screwed to a short pipe welded with ball valve for the discharge of liquid.	

14	The discharge pipe from separator bottom: This is screwed to the union male fitting at the cylindrical base of the separator. It was constructed using a ball valve type welded to a 12 mm diameter stainless steel pipe.	
15	The discharge pipe from separator top: This is screwed to the union male fitting at the conical top of the separator. It was constructed using a ball valve type welded to an 8 mm diameter stainless steel pipe.	

16	Chiller Unit Casing: This was constructed from a 2 mm mild steel plate. The plate was shaped like a cuboid with a bottom and two sides. This encases both the compressor and the evaporator.	
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MODELLING OF INFLOW INTO SHIRORO HYDROPOWER STATION USING ARTIFICIAL NEURAL NETWORK

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Abstract: The stream flow at the Shiroro hydropower reservoir in Nigeria was modelled based on hydro-meteorological parameters using Artificial Neural Network (ANN) software in the 'Alyuda forecaster XL'. Hydro-meteorological data were obtained for a period of 22 years from the hydrologic section of the Shiroro hydropower station in Nigeria was used in model calibration and validation. The data include precipitation (mm), evaporation, temperature (°C) and reservoir inflow (m³/s). Statistical parameters such as Sum of Square Error (SSE), Relative Error (RE), Coefficient of Determination (R²) and correlation coefficient were used to test the performance evaluation of the model. The model revealed positive relationship between the observed and the modelled reservoir inflow with values of correlation coefficient 0.92. The established model was used to predict 20 years streamflow for the hydropower reservoir which was found to have similar statistics with the observed values. The predicted reservoir inflow was subjected to trend analysis which revealed an upward trend with percentage increase of 5.42%. The upward trend is an indication that more water will be availability for hydropower generation at the station.

Key Words: ANN, Inflow, Hydro-meteorological variables, Hydropower and Shiroro

1. INTRODUCTION

Climate change poses threat to renewable hydropower, which continues to play a significant role in energy generation in Nigeria. Hence, the assessment of the impacts of climate change on streamflow is very crucial to hydropower generation and management [1-3]. Artificial Neural Network

(ANN) has been widely applied in modeling of many nonlinear hydrologic processes such as numerical weather and global climate model [4-10]; rainfall-runoff model [11-16]; precipitation prediction [17]; discharge modelling; hydropower energy generation [18-26]; dam break analysis [27-28] and water quality modelling [29-37]. According to Khaing and Thinn [38] among forty eight (48) studies conducted using ANN between 1988 and 1994, Adya and Collopy [39] found that ANN models produced superior results.

The results obtained showed that effectively implemented and validated ANN models performed better than other methods like linear regression, stepwise polynomial regression, multiple regression, discriminant analysis, logic models and rule-based system. A typical neural network architecture consists of three layers of neurons i.e., input, hidden and output layer as shown in Fig. 1 [40].

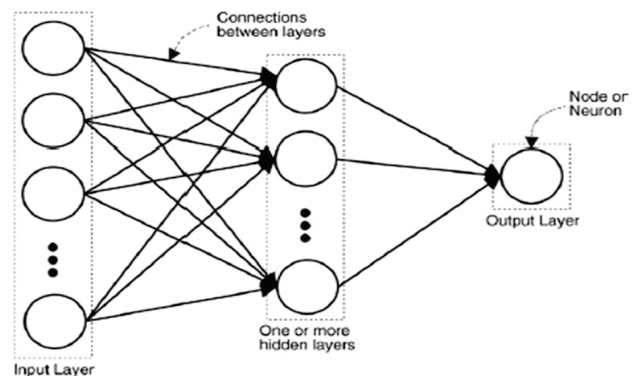


Fig. 1. Artificial neural network architecture [40]

There are various structural neural network architectures commonly employed in linear and non-linear includes: Feed Forward Neural Networks (FFNN), Recurrent Neural Networks (RNN), Convolutional Neural Networks (CNN), Generalized Regression Neural Networks (GRNN), Multilayer Perceptron Neural Networks (MLPNN) and Radial Basis Function Neural Networks (RBFNN)

1.1. Feed Forward Neural Networks

Feed forward Neural Networks (FFNN) refers to the structure where neuron connections flow in one direction only; from a neuron in the input layer to neurons in the hidden layer, or from a neuron in the hidden layer to neurons in the output layer. Importantly, neurons within the same layer are not interconnected with one another. The expression for FFNN is presented in Equation 1 [28].

$$\bar{y}_k = f_o \left[\sum_{l=1}^{M_N} w_{kl} \cdot f_h \left(\sum_{i=1}^{N_N} w_{ji} \cdot x_i + w_{jo} + w_{ko} \right) \right] \quad (1)$$

where:

w_{ji} = weight connecting i th to j th neuron

w_{jo} = bias for the j th hidden neuron

f_h = activation function of the hidden neuron

w_{kj} = weight connects j th neuron in the hidden layer to k th neuron in the output layer

w_{ko} = bias for k th output neuron

f_o = activation function for the output neuron

x_i = i th input value in the input layer and

$\bar{y}_k$ = computed output value

y = observed output value

NN = number of neurons in input layers

MN = number of neurons in hidden layers

It's important to note that the weights differ between the hidden and output layers, and their values are adjusted during the network training process.

1.2. Recurrent Neural Networks

The Recurrent Neural Networks (RNNs) refer to the type of deep models that are optimized to work with sequence data. RNNs are unlike the FFNN in that they are capable of remembering past input in the form of using their internal state (memory) to handle sequences. This property makes RNNs especially applicable in a range of cases like natural language processing, speech recognition, and system modelling of time series where the context and order of data values are important. RNNs are tailored to operate sequential data and they keep a hidden state in which information about previous inputs is recorded. The simplest structure of the RNN is the input layer, a hidden layer and an output layer. In contrast to feed forward neural networks, RNNs have recurrent links, as shown in Figure 2, which allow information to cycle within the network. At each time step, t , the RNN takes an input vector, x_t and updates its hidden state, h_t , using Equation 2.

$$h_t = \sigma_h (W_{xh} x_t + W_{hh} h_{t-1} + b_h) \quad (2)$$

where:

W_{xh} = weight matrix between input and hidden layers

W_{hh} = weight matrix for recurrent connections

b_h and σ_h = bias vector for activation function Which is either the hyperbolic tangent function (tanh) or rectified linear unit.

At each time step, t , the output is computed using Equation 3 [41].

$$y_t = \sigma_y(W_{hy}h_t + b_y) \quad (3)$$

where:

W_{hy} = weight matrix between the hidden and output layers

b_y = bias vector

σ_y = activation function used for the output layer

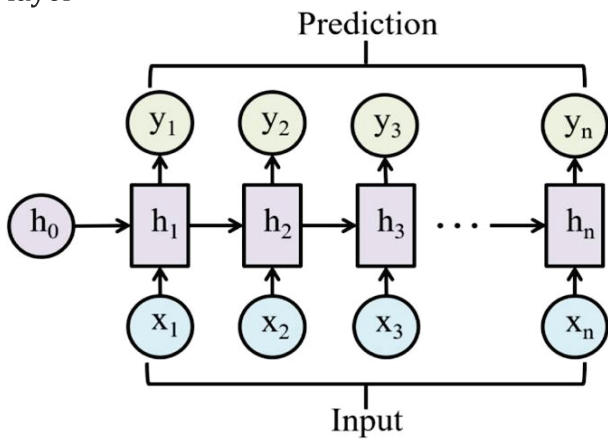


Fig.2. Basic RNN architecture [41]

1.3. Convolutional Neural Networks

Convolutional Neural Network (CNN) refers to an Artificial Neural Network (ANN) that is deep and feed-forward, meaning that they have the impressive generalization capability over other networks that involve fully connected (FC) layers. CNNs are good at learning the most abstracted features of things, especially spatially-dependent data, and can recognize them faster. A deep CNN can be considered as a sequence of layers that step by step learn all kinds of features of the given data (e.g., an image) on different levels of abstraction. The lower layers are designed to learn and extract lower abstraction (high-level) features whereas in the lower layers, learning and extracting features of higher abstraction (low-level) occur. The simplest form of a CNN mechanism is shown in Fig. 3[42].

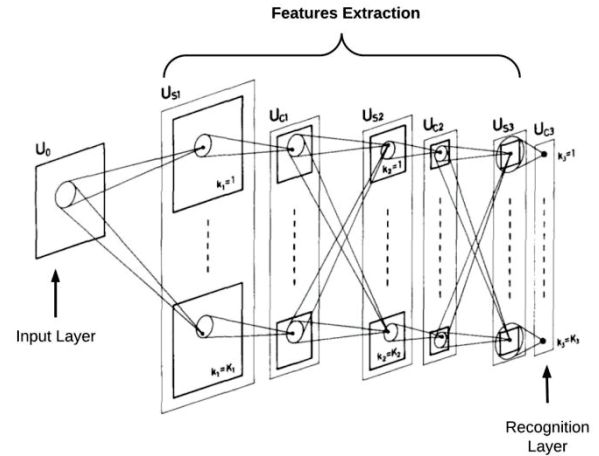


Fig. 3. Basic CNN Architecture [42]

1.4. Generalized Regression Neural Networks

General Regression Neural Network (GRNN) is a relatively new neural structure, the idea of which was created by Specht. Theoretically, it stands out as highly similar to the Multilayer Perceptron Neural Network (MLNN) but there exists an important structural difference between the two constructions. Unlike MLNN, which is used in cases of data classification, where the target variable is a categorical variable, GRNN should be used in regression analysis where the target variable is a continuous variable. Due to its ability to highly depict historical datasets, GRNN is a very viable instrument in respect to predictive modeling. A General Regression Neural Network (GRNN) has four discrete processing layers including the input, design, summation and output layers where the interconnections can be shown in Fig. 4 [40].

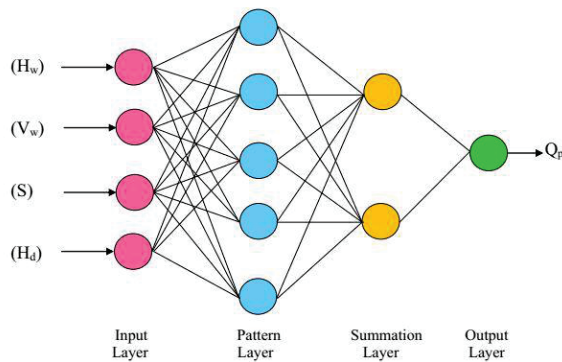


Fig. 4. Structure of GRNN [40]

1.5. Multilayer Perceptron Neural Networks

A multilayer perceptron neural network (MLPNN) is the most commonly used ANN computing technique. The architecture of a typical multilayer neuron is shown in Fig. 5. Basically MLPNN consists of three layers: input, hidden and output. Input layer is a unit where data are introduced to the model, hidden layer is a unit where the data are processed while the output layer is the unit where the result for a given input are produced [43, 49]. Each layer of the MLPNN is made up of several nodes and the layers are interconnected by set of correlation weights. MLPNN was used simulate daily nitrate-nitrogen and suspended sediment fluxes from a small agricultural catchment in the eastern Paris, France with hydro-climatic variables such as streamflow, rainfall, nitrate-nitrogen and suspended sediment as input variables. The results revealed that the MLPNN was able to model nitrate-nitrogen and suspended sediment fluxes accurately [44].

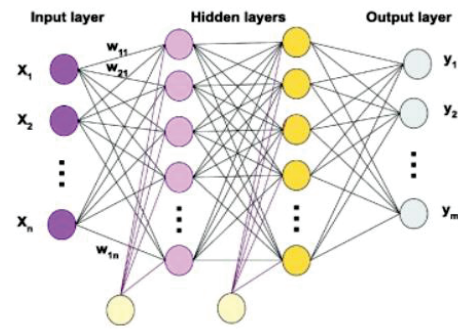


Fig. 5. MLP neural network

1.6. Radial basis function neural network

Radial basis function neural network (RBFNN) is the second ANN modeling architectural technique [45]. It is a supervised and feed forward neural technique. Fig. 6 is the architectural sketch of RBF. It has three layer networks, namely: input, hidden and output. Input layer is a unit where data are introduced to the model, hidden layer is a unit where the data are processed while the output layer is the unit where the result for a given input are produced. The hidden layer consists of a number of nodes and a parameter vector called a 'center' that can be considered as the weight vector. Training of RBF network implies finding the set of basis nodes and weights for the RBF network in order to find the best fit to the trained data.

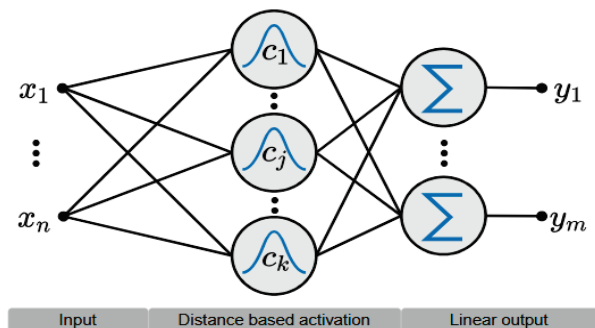


Fig. 6. Radial basis function neural network

The aim of this study is to forecast the inflow into Shiroro hydropower reservoir using hydro-meteorological parameters and ANN. The Shiroro hydropower dam was constructed across River Kaduna in 1990 with installed capacity of 600 MW.

Study Area

Shiroro hydropower plant is a storage-based hydroelectric plant which is situated in the Shiroro Gorge approximately 90 km south-west of Kaduna, on River Dinya with an installed capacity of 600 MW between Latitude $9^{\circ} 46' 35.29''$ and $10^{\circ} 08' 36.65''$ N and Longitude $6^{\circ} 50' 51.23''$ and $6^{\circ} 53' 14.53''$ E [46-48]. The reservoir has a total storage capacity of $7 \times 10^9 \text{ m}^3$ with a surface area of about 320 km^2 and maximum length of 32 m [47]. About 70 % of streamflow into the Shiroro reservoir is from River Kaduna, with other contributions from Rivers Dinya, Sarkin-Pawa, Erena and Muiy [48-50]. The climate of the catchment is similar to the rest of the country. Rainfall in the area is controlled by the tropical maritime air mass. During the dry season the area is dominated by the tropical continental air mass [52]. The rainy season commences in April or May and lasts till October, while the dry season spans between the month of November and March [52]. Mean annual precipitation in the catchment is about 1204.91 mm. Annual temperature around the reservoir varies between 27 and 35°C [52]. The map of the study area is shown in Fig. 7. Google Imagery of the Shiroro Hydropower Plant is presented in Figure 8.

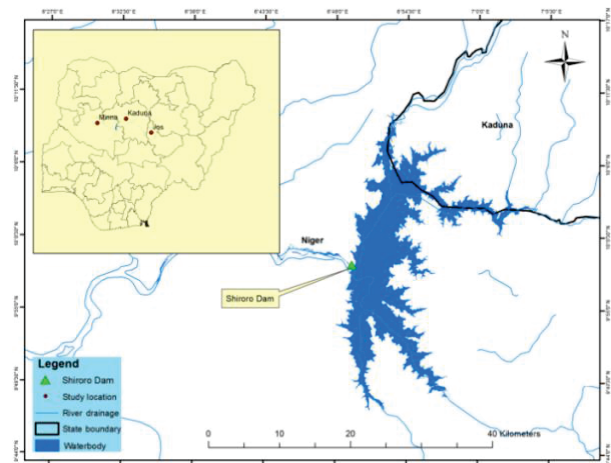


Fig. 7. Map of Shiroro hydropower plant [41]

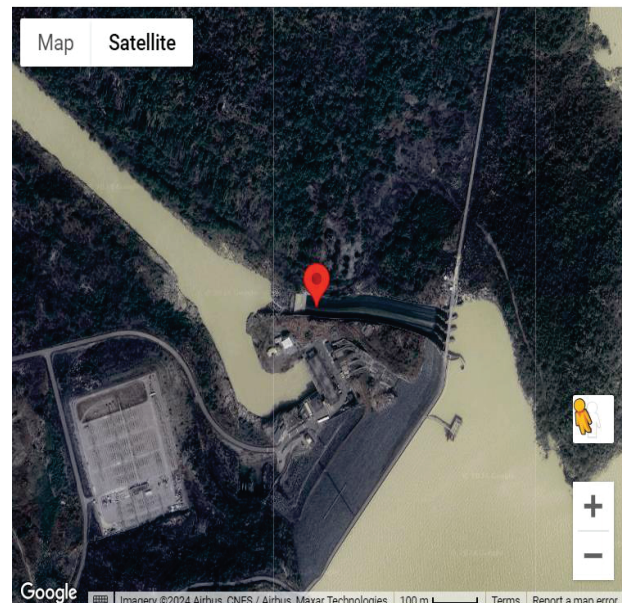


Fig. 8. Google image of Shiroro hydropower plant.

2. MATERIALS AND METHODS

2.1 Data collection

The data required for this study are hydro-meteorological data which were obtained for a period of 22 years from the hydrologic section of Shiroro hydropower station in Nigeria. The data include precipitation (mm), evaporation, temperature ($^{\circ}\text{C}$) and

reservoir inflow (m^3/s). The hydropower station is located on the river Kaduna on Latitude $9^\circ 58' 25''\text{N}$ and Longitude $6^\circ 50' 6''\text{E}$.

2.2 Data analysis

ANN software in the 'Alyuda forecaster XL' was used to model reservoir inflow as a function of meteorological parameters such as precipitation, temperature and evaporation at the station. The model was trained, validated and tested with fourteen, four and five year hydro-meteorological data respectively using error back propagation algorithm in order to speed up its convergence to a minimum error [42]. The developed model was used to predict the monthly inflow from year 2021-2040. The predicted mean monthly inflow was subjected to trend analysis. The mean annual predicted inflow was subjected to percentage variation. Statistical parameters such as Sum of Square Error (SSE), Relative Error (RE), Coefficient of Determination (R^2) and correlation coefficient were used to test the performance evaluation of the model.

3. RESULTS AND DISCUSSION

The summaries of ANN model analysis for the hydro-meteorological parameters at the location is presented in the Table 1, while the comparison between the actual and predicted inflow is depicted in Fig. 9. Also Fig. 10 shows the relationship between actual and predicted inflow. Fig. 11 reveals trend pattern of the predicted inflow. The statistical summary of the predicted inflow is shown in Table 2, while the estimated variation is +5.42%. The trend of the predicted reservoir inflow was also depicted in Figure 11

Table 1: ANN model summary for Shiroro hydropower station

Sample partition	Data (month)	Percentage (%)	SSE	RE	R^2	r
Training	166	63.4	32.53	0.392	0.85	0.9
Validation	48	18.3	8.60	0.417		
Testing	48	18.3		0.294		
Total	262	100				

where:

SSE = Sum of square error

RE = Relative error

R^2 = Coefficient of determination

r = Correlation coefficient

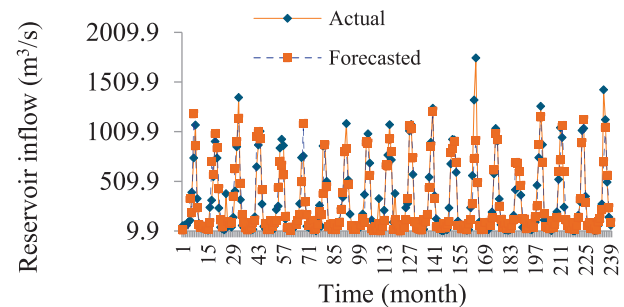


Fig. 9. Actual and predicted inflow for Shiroro hydropwer

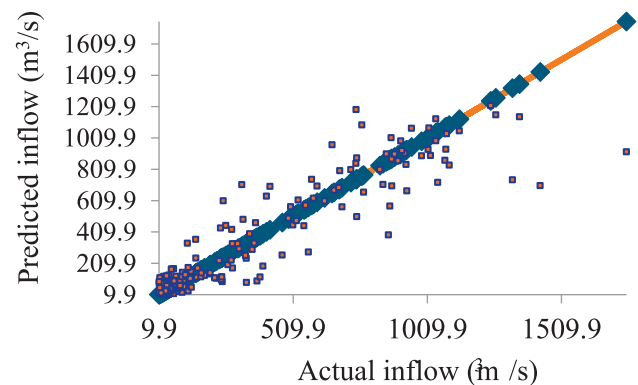


Fig. 10. Scatter plot of predicted and actual inflow

Table 2: Statistical Summary of Predicted Inflow for Shiroro Reservoir (2021-2040)

Parameters	Jan	Feb	Mar	Apr	May	Jun
Mean	26.36	36.65	44.10	47.95	52.15	57.98
Std Dev	7.68	14.48	16.66	16.00	19.19	28.44

CV	0.29	0.40	0.38	0.33	0.37	0.49
Skew	0.52	2.03	1.52	1.73	2.38	3.38
Max	43.26	81.58	87.98	94.82	116.17	167.01
Min	12.96	21.70	23.37	32.35	34.09	38.57

Parameters	Jul	Aug	Sep	Oct	Nov	Dec
Mean	67.86	76.45	74.55	96.66	63.29	44.86
Std Dev	35.09	55.79	20.76	45.56	24.40	27.35
CV	0.52	0.73	0.28	0.47	0.39	0.61
Skew	3.54	4.18	0.68	1.97	1.52	1.98
Max	205.24	308.4	124.3	235.39	134.3	132.1
Min	41.01	51.80	30.35	40.75	32.23	10.68

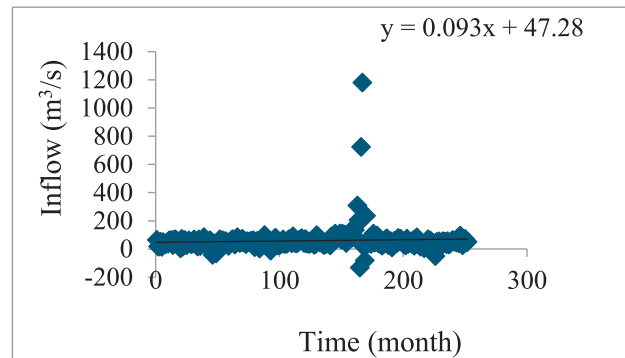


Fig. 11. Trend for predicted reservoir inflow for Shiroro

The summaries of the ANN model results show the percentage of data used for model calibration, validation and testing were 64, 18 and 18 % respectively. R^2 and r were 0.85 and 0.92 respectively which depict a positive and very strong relationship between the actual and the predicted inflow. This implies that the ANN model predicted the inflow into the shiroro reservoir adequately. The mean monthly predicted inflow indicated an upward trend at the station. It can be inferred that more water will be available for hydropower generation in the nearest future. However, adequate reservoir operation mechanisms should put in place to prevent flooding of the communities at the downstream end of the Shiroro hydropower station.

4.CONCLUSION

The ANN model results revealed that there was positive relationship between the actual and forecasted reservoir inflow with fairly high value of correlation coefficient 0.9 and coefficient of determination of 0.85. This shows that the model is appropriate for the reservoir inflow modelling. The predicted reservoir inflow has upward trend, which indicate an increase inflow into the

reservoir in the near future. This will ensure more water for hydropower generation at the stations; however, risk of flooding at stations is envisaged. Therefore, there is need for effective hydropower operation, planning and management to take adequate measures in tackling the envisaged challenges of flood.

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PERFORMANCE MEASURE OF AN IMBALANCED CLASSIFICATION FOR MULTI-CLASS PROBLEMS

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Abstract: Learning and classification are the two processes in data classification. The test data is used to estimate the accuracy of the classification rules, while the pre-classified samples are used by classifier-training system to control the set of variables to be used for proper discrimination. In this study, the performance measure of multiclass problems was examined using the multiclass classification metrics. A 4 X 4 metrics were derived to harmonize inherent sampling distribution in order to complement the prediction of the magnitude of flood along the Foma-river areas. The performance classification was 81%, using the ordered logit regression to examine the significant accuracy of eight (8) variables suspected to have influence on magnitude of flood along Foma river. However, 10% error in classification rule resulting from imbalanced sampling distribution was realized. The error reduction is related to variables that were falsely predicted to be correct in accuracy value (0.8071), which was elicited by the difference in the F1-score value (0.7081) of the multiclass metrics. As a result, six (6) out of the eight(8) classified variables were approximately 71% correctly classified to complement the prediction of magnitude of flood along Foma river areas. This study enabled to demonstrate the derivation of multi-class metrics and its application to address the problem of imbalanced data classification.

Key Words: Data mining, Machine learning, Classifier, Confusion matrix, Measurement metrics

1. INTRODUCTION

The evolution of information technology has resulted in generation of a large volume of documents and massive data in several technical areas. An investigation into such areas has given rise to an approach to manage and operate this valuable data for further decision making [1]. The challenge in decision making tends to emerge when the relations of the dependent variable are based on multiple independent variables. The relationship between the dependent variable and multiple independent variables can be examined to predict the response variable from known independent variables. Typical example are the volumes of sales, prices of stock, and magnitude of flooding, which relations depend on multiple predictor variables. Regrettably, numerous world problems are not just predictions [2].

However, relationship between variables can be classified and modelled such that the dis-

parity in the class distribution will be considered in the data analysis. One of the main task of machine learning is the idea of classifying an input into outcomes, such as;

'Male' or 'Female', 'Pass' or 'Fail', 'Yes' or 'No', and so on? [3]. The confusion matrix for binary classification cells has True Positives (TP)— the number of positive that were correctly classified as such by the classifier, True Negatives (TN)— the number of negatives that were correctly classified as such by the classifier, False Positive (FP)— the number of positive that were classified as negatives by the classifier. False Negative (FN)— number of negatives that were classified as positives by the classifier [4]. But certainly, there are problems that input can be classified as one of many outputs, such as weather; 'Sunny', 'Cloudy', 'Rain', and 'Snow'. Other can be Magnitude of flood; 'Extreme', 'Severe', 'Moderate', and 'Mild'. In other to solve multiclass problems, there is a need to determine how well a classifier has predicted the outcomes [5].

2. PROBLEM STATEMENT AND DATA GENERATION

Several cases of flooding of urban cities in Nigeria have been reported in the north-central part of Nigeria. As reported in The Nigeria Tribune newspaper [6], "Flood damages property in Ilorin", where many residential buildings were reported to have submerged after a protracted rain that lasted for hours. This study examined the magnitude of flood along Foma river. The river is located in the Ilorin West Local Government of Kwara state, Nigeria on latitude N08,49574 and longitude E004,5107, and a distance of 7 km to the Emir palace Ilorin. During the rainy season, the river is freely flowing, while it is quiet flowing during the dry season. The catchment area of the river is estimated to be around 303,309,421.02 square meters. The river, especially during the rainy season, overflows its bank, which over the years had resulted in several kilometers stretch of floodplains. The human encroachment into the floodplain had triggered several damages to buildings, institutions, and other social facilities in the affected communities [7].

This study made use of the watershed composition to carry out the classification of the magnitude of flood along the river, using the Standard Precipitation Index (SPI) narratives. The hydrological analysis revealed the degrees of the flood were varied along the watersheds. The procedures involve numerical data about intrusion, runoff dynamics and determine the conceptual research approach adopted in the study. The variables have some peculiar characteristics that dictate the direction of flow of flood along the Foma river rather than just a prediction through generalization which may not be so accurate. The surface area from which runoff resulting from rainfall is collected and drained along Foma river areas are presented in the Fig. 1.

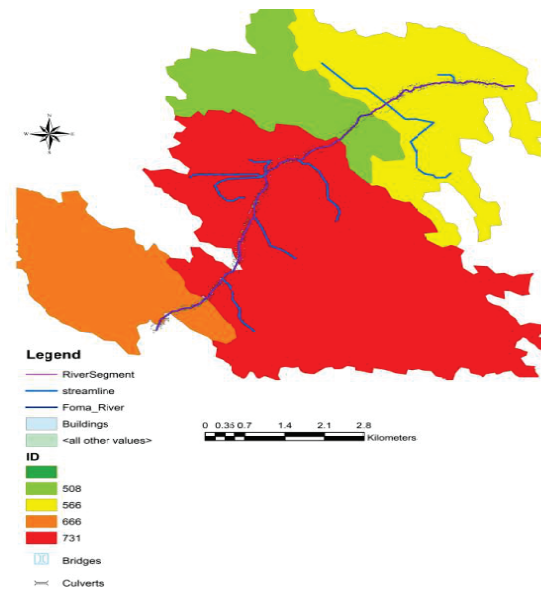


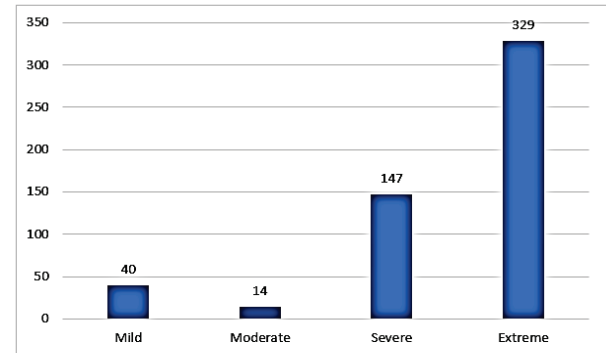
Fig. 1. Foma river watersheds

Consequently, the magnitude of flood was classified as mild, moderate, severe, and extreme flooding around the river areas. Table 1 presents the eight cross-section variables that were derived along the watersheds through the application of GIS and site observation.

Table 1: Cross-sectional Variables from Foma river Areas

Variable Name	Task	Values	Data Type
River Watershed	Input	Shed1, Shed2, Shed3, Shed4	Nominal
Drainage Density	Input	0.0001, 0.0002, 0.0005, 0.0007	Ordinal
Vulnerable Status of structures	Input	Not Vulnerable, Fairly Vulnerable, Highly Vulnerable	Ordinal
Types of Vulnerable Structures	Input	Hospital, Police post, Fishery ponds, Abattoir, Educational, Commercials, Slum, Agriculture, Residentials	Nominal
Bridges or Culverts	Input	CAIS, Apalara, Oke-foma, Foma-bridge, Ajetunmobi, Oloje-bridge, Abata Baba-oyo, Alagbado Bridge, Sobi-bridge	Nominal
Size of Bridges or Culvert (m)	Input	2.1, 4.5, 7.2, 11.2, 14.9, 15, 19.5, 60.8	Ordinal
River Point	Input	Source, Middle, Extreme, Terminal	Nominal
River Pollution	Input	Fair, High, Severe, Extreme	Ordinal
Magnitude of Flood	Target	Mild, Moderate, Severe, Extreme	Ordinal

However, there were indications of high disparity in the magnitude of flooding along the 530 structures in Foma river areas. Figure 2 demonstrates the level of sampling disparity in the study.

**Fig. 2.** Level of magnitude of flood along Structures of the Foma river areas

Thus, the prediction of the magnitude of flood along these areas will tend to favour the higher categories compared to the lower categories. Therefore, there is the need to further describe the classification performance of the techniques used in this study.

3. THEORETICAL BACKGROUND AND METHODOLOGICAL APPROACH

This study was able to categorize the watersheds along the Foma river into 4 categories. Based on this, the magnitude of floods were classified as mild = 0, moderate =1, severe = 2, and extreme = 3, along each of the categories. While 530 structures captured by the Geographical Information System (GIS) along these watersheds are the observation in the data set for the study.

To ensure every observation in the dataset has a chance of appearing in training and test set, the study employed the use of tenfold cross-validation evaluation technique. The process is repeated until every k-fold serves as the test set, such that the average record scores become the performance metric of the model. The cross-validation technique in the study is shown in Fig. 3

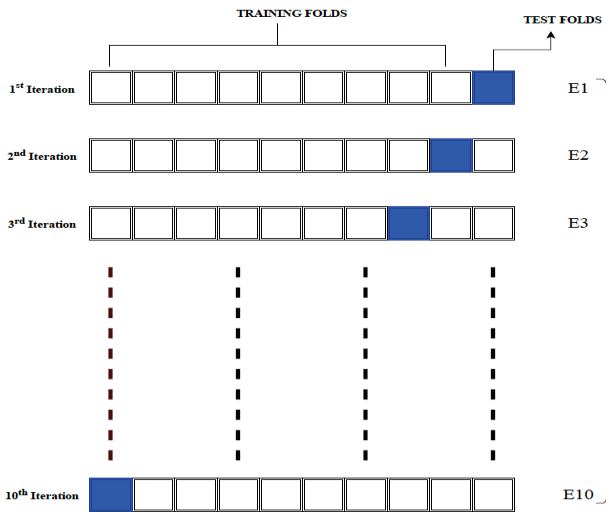


Fig. 3. Cross-validation technique in the study

$$\text{where, } E = \frac{1}{10} \sum_{i=1}^{10} E_i \quad (1)$$

Most analyses are based on estimating models of which response variable Y is a continuous outcome, and regressed on independent variable X . But in case Y is not continuous, otherwise digital and ordered variables, such that cross thresholding this underlying variable leads to the values of the observed ordinal variable Y to change. We can understand the fundamental interval of Y , but not its exact value. In this case ordinal regression can estimate the effects of X 's on the fundamentality of Y [8].

Ordered response models usually applied when the dependent variable is discrete and ordered measurement. In general, let's consider an ordered response variable Y , which can take the value $Y+1, 0, 1, 2, \dots, j$. Such that the general linear function:

$$\hat{Y} = X\beta + \varepsilon \quad (2)$$

The magnitude of flood and its relationship with the eight (8) cross-sectional variables can be established using equation 3.

$$P(\text{event}) = \frac{e^Z}{1 + e^Z} \quad (3)$$

The probability of occurrence P is between 0 and 1, as the Z value falls between $-\infty$ and $+\infty$. The linear combination of the cross-sectional variables with the magnitude of flood is indicated in equation 4, where β_o is the cutoff value.

$$Z = \beta_o + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n \quad (4)$$

This is such that the general equation of a logistic regression model is given by (Gasso, 2019) equation 5.

$$Y = \text{logit } P = \left[\frac{P}{1-P} \right] = \beta_o + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n \quad (5)$$

The latent variable Y is not directly observed. Thus, the threshold set by which the observed value change as the predicted, otherwise known as 'cut point'. In this case, the relationship between the predicted magnitude of flood ($\hat{Y}$) and the observed magnitude of flood (y) are established below. let α_i be the threshold. So that.

$$Y = \begin{cases} Y_0 & \text{iff } \hat{Y} < \alpha_0 \\ Y_1 & \text{iff } \alpha_0 \leq \hat{Y} \leq \alpha_1 \\ Y_2 & \text{iff } \alpha_1 \leq \hat{Y} \leq \alpha_2 \\ Y_3 & \text{iff } \hat{Y} \geq \alpha_2 \end{cases} \quad (6)$$

In order to apply the models in Gretl software, the dependent variable must either take only non-negative integer values or be explicitly marked as discrete. By underlying assumptions, ordered logistic regression considered the relationship between separate pairs of groups' outcomes as the same. By implication, the coefficients that define each relationship between the lowest, concerning all other higher categories of the classified magnitude of flood are also the same compared to the next lower category and another corresponding higher category. The relationship is being defined

as the parallel regression assumption or proportion odd assumption. However, the significance of the classification technique by the ordered logistic regression analysis of the cross-sectional variables will be further exposed to confusion metrics in order to describe how well this approach has carried out the classification within the classes.

3.1 Determining the Classification Error

Based on the categorization of the magnitude of flood into four classes, the metrics values were determined through the error classification table, known as **CONFUSION MATRIX**. The multi-class confusion matrix describes the performance of a multi-class classification and portrayed the classification at glance for proper analysis. In this study, the multi-class confusion matrix for the classification of the magnitude of flood along the Foma-river is given in Table 2.

Table 2: Multi-class Classification of Magnitude of Flood in the Study

Observed	Predicted			
	Mild	Moderate	Severe	Extreme
Mild	P_{mm}	P_{dm}	P_{sm}	P_{em}
Moderate	P_{md}	P_{dd}	P_{sd}	P_{ed}
Severe	P_{ms}	P_{ds}	P_{ss}	P_{es}
Extreme	P_{me}	P_{de}	P_{se}	P_{ee}

The visualization table comprises two sections, which is the observed classification section and the predicted classification section. Both sections have four subsections for each of the classes. To calculate these metrics, there is a need to define the variables in the visualization Table 2 above.

P_{mm} : This is the variable that represents the number of predictions where mild flooding was correctly classified as mild flooding. This is also the true positive for the mild flooding class.

P_{dm} is the variable that represents the number of predictions where mild flooding was incorrectly classified as moderate flooding.

P_{sm} is the variable that represents the number of predictions where mild flooding was incorrectly classified as severe flooding.

P_{em} is the variable that represents the number of predictions where mild flooding was incorrectly classified as extreme flooding.

P_{md} is the variable that represents the number of predictions where moderate flooding was incorrectly classified as mild flooding.

P_{dd} represents the number of predictions where moderate flooding was correctly classified as moderate flooding. This is also the true positive of the moderate flooding class.

P_{sd} is the variable that represents the number of predictions where moderate flooding was incorrectly classified as severe flooding.

P_{ed} is the variable that represents the number of predictions where moderate flooding was incorrectly classified as extreme flooding.

P_{ms} represents the number of predictions where severe flooding was incorrectly classified as mild flooding.

P_{ds} is the variable that represents the number of predictions where severe flooding was incorrectly classified as moderate flooding.

P_{ss} is the variable that represents the number of predictions where severe flooding was correctly classified as severe flooding. This is also the true positive of the severe flooding class.

P_{es} represents the number of predictions where severe flooding was incorrectly classified as extreme flooding.

P_{me} is the variable that represents the number of predictions where extreme flooding was incorrectly classified as mild flooding.

P_{de} is the variable that represents the number of predictions where extreme flooding was incorrectly classified as moderate flooding.

P_{se} is the variable that represents the number of predictions where extreme flooding was incorrectly classified as severe flooding.

P_{ee} represents the number of predictions where extreme flooding was correctly classified as extreme flooding. This is also the true positive of the extreme flooding class.

In the multi-class measurement, errors in prediction have different implications. Errors in predicting Y as X may likely to have differently weighted implication than predicting C as D , and many more of such errors. Accuracy measure does not take any of such problems into account. The pre-determined assumption was that sample distribution among classes are balanced. Thus, in the case of imbalance distribution, the most used classifier repeatedly produces a disappointing estimate [9]. Thus, the common classifier needs to be re-examined to address the problem of imbalanced data classification. This study made use of accuracy, precision, recall and F1-score. Which were defined by TRUE POSITIVE (TP), TRUE NEGATIVE (TN), FALSE POSITIVE (FP) and FALSE NEGATIVE (FN).

$$\text{Accuracy} = \frac{TP}{(TP+FP+TN+FN)} \quad (7)$$

$$\text{Precision} = \frac{TP}{(TP+FP)} \quad (8)$$

$$\text{Recall} = \frac{TP}{(TP+FN)} \quad (9)$$

$$\text{F1-Score} = 2 \times \frac{\text{Precision} \times \text{Recall}}{(\text{Precision} + \text{Recall})} \quad (10)$$

These metrics were used to examine the influences of harmonic mean of precision and recall in the process of adjusting the inherent sampling distribution along the course of offering prediction of the magnitude of flood along the Foma-river. Table 3 demonstrated the processes in generating the true positive estimate.

Table 3: Generation of the True Positive Estimate

Actual Y	Predicted $\hat{Y}$				Marginal Total $Y_{i.}$
	$\hat{Y}=0,$ $\hat{P}=1$	$\hat{Y}=1,$ $\hat{P}=1$	$\hat{Y}=2,$ $\hat{P}=1$	$\hat{Y}=3,$ $\hat{P}=1$	
	0	1	2	3	
0	$Y=\hat{Y}$	$Y \neq \hat{Y}$	$Y \neq \hat{Y}$	$Y \neq \hat{Y}$	$Y_{0.}$
1	$Y \neq \hat{Y}$	$Y=\hat{Y}$	$Y \neq \hat{Y}$	$Y \neq \hat{Y}$	$Y_{1.}$
2	$Y \neq \hat{Y}$	$Y \neq \hat{Y}$	$Y=\hat{Y}$	$Y \neq \hat{Y}$	$Y_{2.}$
3	$Y \neq \hat{Y}$	$Y \neq \hat{Y}$	$Y \neq \hat{Y}$	$Y=\hat{Y}$	$Y_{3.}$
Marginal Total $Y_{.j}$	$Y_{.0}$	$Y_{.1}$	$Y_{.2}$	$Y_{.3}$	Grand Total $Y_{..}$

This is the addition of all the diagonal elements in the matrix divided by the overall total of the matrix. The diagonal elements represent a situation where the predicted values tally with observed values:

1) True Positive (TP) = Addition of all the shaded cells (11)

To generate the true negative value, each class of the distribution will be estimated, such that the class 0 true negative estimate was estimated using Table 4.

Table 4: Generation of the True Negative Estimate for Class 0

Actual Y	Predicted $\hat{Y}$				Mar- ginal Total Y_i
	$\hat{Y}$ =0, $\hat{P}=1$	$\hat{Y}$ =1, $\hat{P}=1$	$\hat{Y}$ =2, $\hat{P}=1$	$\hat{Y}$ =3, $\hat{P}=1$	
	0	1	2	3	
0	$Y=\hat{Y}$	$Y\neq\hat{Y}$	$Y\neq\hat{Y}$	$Y\neq\hat{Y}$	Y_0
1	$Y\neq\hat{Y}$	$Y=\hat{Y}$	$Y\neq\hat{Y}$	$Y\neq\hat{Y}$	Y_1
2	$Y\neq\hat{Y}$	$Y\neq\hat{Y}$	$Y=\hat{Y}$	$Y\neq\hat{Y}$	Y_2
3	$Y\neq\hat{Y}$	$Y\neq\hat{Y}$	$Y\neq\hat{Y}$	$Y=\hat{Y}$	Y_3
Mar- ginal Total Y_j	$Y_{.0}$	$Y_{.1}$	$Y_{.2}$	$Y_{.3}$	Grand Total $Y_{..}$

$$2(a) \text{ True negative for class 0} \\ = \frac{\text{Addition of all shaded cells}}{\text{Number of Classes}} \quad (12)$$

To generate the true negative estimate for class 0, all the elements in the matrix will be added except the row and column elements of the class 0. The summation of these elements is divided by the number of classes in the matrix. Similarly, the class 1 true negative estimate was generated using Table 5.

Table 5: Generation of the True Negative Estimate for Class 1

Ac- tual Y	Predicted $\hat{Y}$				Marginal Total Y_i
	$\hat{Y}$ =0, $\hat{P}=1$	$\hat{Y}$ =1, $\hat{P}=1$	$\hat{Y}$ =2, $\hat{P}=1$	$\hat{Y}$ =3, $\hat{P}=1$	
	0	1	2	3	
0	$Y=\hat{Y}$	$Y\neq\hat{Y}$	$Y\neq\hat{Y}$	$Y\neq\hat{Y}$	Y_0
1	$Y\neq\hat{Y}$	$Y=\hat{Y}$	$Y\neq\hat{Y}$	$Y\neq\hat{Y}$	Y_1

2	$Y\neq\hat{Y}$	$Y\neq\hat{Y}$	$Y=\hat{Y}$	$Y\neq\hat{Y}$	Y_2
3	$Y\neq\hat{Y}$	$Y\neq\hat{Y}$	$Y\neq\hat{Y}$	$Y=\hat{Y}$	Y_3
Mar- ginal Total Y_j	$Y_{.0}$	$Y_{.1}$	$Y_{.2}$	$Y_{.3}$	Grand Total $Y_{..}$

$$2b) \text{ True negative for class 1} \\ = \frac{\text{Addition of all shaded cells}}{\text{Number of Classes}} \quad (13)$$

To generate the true negative estimate for class 1, all the elements in the matrix were added except the row and column elements of class 1. The summation of these elements is divided by the number of classes in the matrix. The true negative estimate for class 2 of the confusion matrix was estimated using the methodology in Table 6.

Table 6: Generation of the True Negative Estimate for Class 2

Ac- tual Y	Predicted $\hat{Y}$				Mar- ginal Total Y_i
	$\hat{Y}$ =0, $\hat{P}=1$	$\hat{Y}$ =1, $\hat{P}=1$	$\hat{Y}$ =2, $\hat{P}=1$	$\hat{Y}$ =3, $\hat{P}=1$	
	0	1	2	3	
0	$Y=\hat{Y}$	$Y\neq\hat{Y}$	$Y\neq\hat{Y}$	$Y\neq\hat{Y}$	Y_0
1	$Y\neq\hat{Y}$	$Y=\hat{Y}$	$Y\neq\hat{Y}$	$Y\neq\hat{Y}$	Y_1
2	$Y\neq\hat{Y}$	$Y\neq\hat{Y}$	$Y=\hat{Y}$	$Y\neq\hat{Y}$	Y_2
3	$Y\neq\hat{Y}$	$Y\neq\hat{Y}$	$Y\neq\hat{Y}$	$Y=\hat{Y}$	Y_3
Mar- ginal Total Y_j	$Y_{.0}$	$Y_{.1}$	$Y_{.2}$	$Y_{.3}$	Grand Total $Y_{..}$

2c) True negative for class 2

$$= \frac{\text{Addition of all the shaded cells}}{\text{Number of Classes}} \quad (14)$$

To generate the true negative estimate for class 2, all the elements in the matrix will be added except the row and column elements of class 2. The summation of these elements is divided by the number of classes in the matrix. The methodology in Table 7 reflected how the negative estimate for class 3 of the confusion matrix in multi-class was generated.

Table 7: Generation of the True Negative Estimate for Class 3

Actual Y	Predicted $\hat{Y}$				Marginal Total $Y_{i.}$
	$\hat{Y}=0, \hat{P}=1$	$\hat{Y}=1, \hat{P}=1$	$\hat{Y}=2, \hat{P}=1$	$\hat{Y}=3, \hat{P}=1$	
	0	1	2	3	
0	$Y=\hat{Y}$	$Y \neq \hat{Y}$	$Y \neq \hat{Y}$	$Y \neq \hat{Y}$	$Y_{0.}$
1	$Y \neq \hat{Y}$	$Y=\hat{Y}$	$Y \neq \hat{Y}$	$Y \neq \hat{Y}$	$Y_{1.}$
2	$Y \neq \hat{Y}$	$Y \neq \hat{Y}$	$Y=\hat{Y}$	$Y \neq \hat{Y}$	$Y_{2.}$
3	$Y \neq \hat{Y}$	$Y \neq \hat{Y}$	$Y \neq \hat{Y}$	$Y=\hat{Y}$	$Y_{3.}$
Marginal Total $Y_{.j}$	$Y_{.0}$	$Y_{.1}$	$Y_{.2}$	$Y_{.3}$	Grand Total $Y_{..}$

2d) True negative for class 3

$$= \frac{\text{Addition of all the shaded cells}}{\text{Number of Classes}} \quad (15)$$

To generate the true negative estimate for class 3, all the elements in the matrix were added except the row and column elements of class 3. The summation of these elements is divided by the number of classes in the matrix.

Generally, the estimate for True negative

$$= 2a + 2b + 2c + 2d \quad (16)$$

To generate the false-positive estimate, all the elements in the column were added except the true positive of the class. The summation of each class was divided by the number of classifications in each class. Table 8 demonstrated how false positive estimate was generated.

Table 8: Generation of the False Positive Estimate

Actual Y	Predicted $\hat{Y}$				Marginal Total $Y_{i.}$
	$\hat{Y}=0, \hat{P}=1$	$\hat{Y}=1, \hat{P}=1$	$\hat{Y}=2, \hat{P}=1$	$\hat{Y}=3, \hat{P}=1$	
	0	1	2	3	
0	$Y=\hat{Y}$	$Y \neq \hat{Y}$	$Y \neq \hat{Y}$	$Y \neq \hat{Y}$	$Y_{0.}$
1	$Y \neq \hat{Y}$	$Y=\hat{Y}$	$Y \neq \hat{Y}$	$Y \neq \hat{Y}$	$Y_{1.}$
2	$Y \neq \hat{Y}$	$Y \neq \hat{Y}$	$Y=\hat{Y}$	$Y \neq \hat{Y}$	$Y_{2.}$
3	$Y \neq \hat{Y}$	$Y \neq \hat{Y}$	$Y \neq \hat{Y}$	$Y=\hat{Y}$	$Y_{3.}$
Marginal Total $Y_{.j}$	$Y_{.0}$	$Y_{.1}$	$Y_{.2}$	$Y_{.3}$	Grand Total $Y_{..}$
	FP0	FP1	FP2	FP3	

$$3) \text{ False positive} = \frac{FP0+FP1+FP2+FP3}{\text{Number of Classes}} \quad (17)$$

The false-negative estimate is generated by adding all the elements in a row except the true positive of that class. The addition of all the corresponding estimates of the rows is divided by the number of classes in the matrix as demonstrated in Table 9.

Table 9: Generation of the False Negative Estimate

Actual Y	Predicted $\hat{Y}$					Mar- ginal Total Y_i .	
	$\hat{Y}$ =0, $\hat{P}=1$	$\hat{Y}$ =1, $\hat{P}=1$	$\hat{Y}$ =2, $\hat{P}=1$	$\hat{Y}$ =3, $\hat{P}=1$	Mar- ginal Total Y_i .		
	0	1	2	3			
0	Y= $\hat{Y}$	Y≠ $\hat{Y}$	Y≠ $\hat{Y}$	Y≠ $\hat{Y}$	Y ₀ .	FN0 FN1 FN2 FN3	
1	Y≠ $\hat{Y}$	Y= $\hat{Y}$	Y≠ $\hat{Y}$	Y≠ $\hat{Y}$	Y ₁ .		
2	Y≠ $\hat{Y}$	Y≠ $\hat{Y}$	Y= $\hat{Y}$	Y≠ $\hat{Y}$	Y ₂ .		
3	Y≠ $\hat{Y}$	Y≠ $\hat{Y}$	Y≠ $\hat{Y}$	Y= $\hat{Y}$	Y ₃ .		
Mar- ginal Total Y _j	Y _{·0}	Y _{·1}	Y _{·2}	Y _{·3}	Gran- d To- tal Y _{..}		

$$4) \text{ False negative} = \frac{FN0+FN1+FN2+FN3}{\text{Number of Classes}} \quad (18)$$

4 PERFORMANCE MEASURE AND CLASSIFICATION ERRORS OF THE

ORL MODEL

The performance classification was carried out using the ordered logistic regression approach. The 10-folds cross-validation estimates of the model are given in Table 9.

Table 9: Performance Classification of the Models

THE FOLDS	PERFORMANCE CLASSIFICATIONS
Fold 1	80.7
Fold 2	80.5
Fold 3	80.5
Fold 4	80.5
Fold 5	80.3
Fold 6	81.1
Fold 7	81.3

Fold 8	80.1
Fold 9	81.6
Fold 10	80.3
Average	80.7 %

It was observed that the average classification accuracy is approximately 81%. By this impression, the model is said to be 81% correctly prescribed to complement the prediction of the magnitude of flood along River Foma. However, this measure tends to favour the higher classes compared to the lower classes due to the imbalance distribution in the classification of the magnitude of flood along the Foma river areas.

In order to regulate the imbalanced classification from OLR model, this study made use of the multiclass metrics derived to harmonise the mean of precision and recall and obtain the measurement metrics in Table 10.

Table 10: The Values of the Measurement Metrics

Models	Measurement Metrics			
	Accu- racy	Precision	Recall	F1-score
Aver- age Values	0.8071	0.8026	0.638 6	0.7081

The average values of each of the multi-class metrics derived in Table 10 were directed towards describing each of the metrics to the model prediction and consequences of the imbalanced sampling distribution.

The Accuracy's Description

The average value of the accuracy metric is approximately 80.7%. This estimate suggested a very high predictive estimate and gives the recognition rate of the classifier which gives the percentage of the observations that were classified correctly in the OLR model.

The Precision's Description

The average value of this metric description of the OLR model is approximately 80.3%. This value represents the proportion of the correct positively predicted variables relative to variables that are positively predicted. This metric is investigating the fact that of all variables in the model that were correctly predicted, how many of the variables were indeed predicted correctly? The metric estimate had responded by putting forward that approximately 80% of the variables were predicted correctly.

The Recall's Description

Recall reflected the proportion of which class of the variables that were correctly predicted and hoping that the classifier will detect such proportion. However, in this study, the classifier was able to detect approximately 63.9% of the proportion of the class that were predicted correctly. This metric's prediction was able to streamline the disparities between the estimates of accuracy and precision that was incorrectly inherited from the imbalance sampling distribution.

The F1-score's Description

Finally, the F1-score average value in this study is approximately 70.8%. This value takes into recognition both the false-negative and the false positive in the confusion matrix and regulates the imbalanced sampling distribution inherent in the study. The metric has also been able to put a relatively high estimate of the accurate description in check, due to the harmonization of the precision value (0.8026) and recall value (0.6386), which

has provided the F1-score value (0.7081). Indeed, a 10% reduction relating to factors that were falsely predicted to be correct on OLR value (0.8071) in the study was realized.

4 CONCLUSION AND RECOMMENDATIONS

The study has demonstrated how a multi-class measurement metrics can be generated from a confusion matrix. Estimates from the matrix has been used to visualize and describe the performance classification of magnitude of flood along Foma river using the OLR. The pre-classified accuracy of the model was estimated to be approximately 81%, which demonstrated a very good classification for the model. But, due to an imbalanced sample, the need to re-examine the performance of the classification arises.

A multi-class metrics was generated to harmonise the imbalances in the sample distribution and reduce the error components purportedly inherited. Consequently, 10% error reduction was achieved from the difference in OLR model value (0.8071) and F1-score value (0.7081). The reduction is related to the factors that were predicted falsely to be correct in the study.

This study has examined the performance of ordered logistic regression in the classification of imbalanced cross-sectional variables along the Foma river areas. The study also described how well the OLR has classified the imbalanced variables using the multiclass matrix. This procedure further elicited the need to examine the sampling distribution and ensure relevant measure is carried out in the process of data classification.

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DESIGN AND PERFORMANCE EVALUATION OF A REVERSED ABSORBER-ENHANCED, PASSIVE, INDIRECT SOLAR DRYER

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Abstract: solar thermal devices have for decades offered a viable alternative for heating which is both cheap and pollution free. However due to the intermittent nature of the sun and the challenge of obtaining high grade heating from these devices, the adoption of such technology appears to be low. The current work evaluated the performance of a passive solar dryer that had been enhanced using a reversed absorber system. By adopting a unique chimney design, adequate air draft was achieved within the dryer. Results showed that the dryer was able to generate up to 10°C temperature difference between the ambient and the drying cabinet at peak solar hours. The 2°C temperature drop observed between the collector's outlet and drying chamber was attributed to the poor insulation achieved by the ply board walls, however, this ensured that the dryer's overall cost remained low. The instantaneous efficiency plot showed that the dryer had performances superior to existing plane passive solar dryers, maintaining a base efficiency value of 37% at no load. This impressive performance testifies to the efficacy of the reversed absorber set up in boosting the performance of passive dryers while maintaining a low cost profile.

Key Words: Solar dryer, reversed absorber, renewable energy, performance evaluation, solar chimney

1. INTRODUCTION

The global demand for energy has been on the rise for several decades. The International Energy Outlook 2019 projects that world energy consumption would grow by nearly 50% between 2018 and 2050[1]. This surge in energy demand is driven by industrialization and population growth, especially in emerging economies[2]. Owing to the finite nature of the conventional energy sources, it is obvious that this pattern of energy consumption is not sustainable[3]. Attention has therefore been given by researchers to various forms of renewable energy as a sustainable and environmentally friendly source of meeting global energy needs[4]. In recent years, Solar energy is recognized as one of the most promising alternative energy sources because of its abundance and relatively low cost of power gen-

eration[5]. Many systems have been developed to harness both the thermal and photovoltaic energies from the sun with focus on increasing efficiency, cost reduction and storage, since solar energy largely fluctuates with time and seasonal changes[6–8].

Solar drying is a renewable energy-based solution to the drying of agricultural produce. Preservation of farm produce is a major challenge facing most subsistent farmers. Owing to the cost of accessing conventional dryers and the lack of steady electricity, these farmers are forced to sell off their products at a less profitable price when sundried or face the loss of a good part of them. For this reason, efforts are made to improve the efficiency of solar dryers, so as to meet the needs of these farmers better. Ekechukwu and Norton [9] conducted a detailed review on different designs construction and principles of operation of a wide variety of Solar

air heaters (SAH) for drying, and broadly classified them under; active, passive and hybrid SAHs according to their Mode of heating. A typical Active solar air heating system depends solely on solar energy as a heating source then employs electric pumps or fans for cooling. Thus, by their operation for air circulation, active solar air heaters are also forced convection heating systems. Passive SAHs on the other hand is conventionally termed natural-circulation solar drying system. As they do not require pumps or fans for air circulation, more attention is needed in their design to ensure air circulation.

Further classifications are made with respect to the configuration of air flow around the absorber plate. In this case, they can be classified as single pass [10] and double pass solar air heaters [11]. In single pass systems, there is a unidirectional flow of air, either above or below the absorber plate, from air inlet to outlet. While in double pass heaters, air flows in two directions, either parallel or counter directions above below/ and above the absorber plate. Modifications for heat storage can be considered as well for classification, in which case there are SAHs with and without energy storage unit [12–14]. In solar air heaters with heat storage units, phase change materials (PCM) are incorporated to store thermal energy during the day and release it for use in the night hours.

Reversed side solar air heating collector is employed in integral passive (indirect) type solar air heaters. It is mostly applied in drying of agricultural products when direct exposure to sunlight would produce adverse effects such as discoloration, reduction in product quality and consequent failure to meet international standards [15]. Researchers have done several studies using the re-

versed absorber solar air collector. One of the earlier studies was done by Goyal and Tiwari (1996) [16] who carried out a parametric study of a reversed flat plate absorber cabinet drier. Energy balance equations for the system were solved to obtain its thermal performance. The new system was compared with the conventional flat plate drier and it was observed that it operated for longer hours because of minimum bottom and top heat losses. Also the system had a higher crop temperature because of the maximum utilization of the available solar energy. Vijay, Khawale, Shashank B. Thakare [17] conducted a modeling and experimental studies on forced circulation, single glazing solar crop dryer coupled with reversed absorber type solar air heater. A solar dryer using double absorber with reflector and single solar air heater was designed. A significant increase in the collector efficiency, dry efficiency and pick-up efficiency was recorded. The mathematical model for dried chili in solar drying was also developed [18] developed a two-tray reverse absorber cabinet dryer with glass cover. The system combines the conventional cabinet drier design that allows insolation from the top thereby heating the upper tray and a reverse absorber unit. The objective was to determine the thermal performance of the unit. Their conclusion was that glass could be used as the drying chamber roof, especially when the direct exposure of the products to sun has little or no effect to the desired output. However, it was observed that the overall system efficiency decreased by using such glass top. Dilip Jain (2007) [19] developed a similar transient analytical model to examine the performance of a reversed absorber with packed bed thermal storage natural convection solar crop dryer. A packed bed

made of Pebbles and granite grits were used as heat storage materials under the two absorbers. It was concluded that the width of air flowing channel and height of the packed bed had a significant effect on crop temperature and that packed bed materials assisted in reducing fluctuation in crop temperature during non-shine hours of the day. The model developed was useful for predicting the crop temperature, moisture content and drying rate of the crops.

A significant knowledge gap with these works is the evaluation of a drying system modified to be enhanced with a reversed absorber without needing either a heat storage system or a forced convection system which all add to the overall cost of the system, making it unaffordable for most rural farmers. This current work therefore seeks to design and conduct a performance evaluation of such a system.

2. MATERIALS AND METHODS

In this section, the details of the designed dryer and the experimental procedure and set up for its performance evaluation are presented.

2.1. Design of the Dryer

As noted by [9] above, special attention must be paid to the air flow of the system in consideration as there will be no extra driving force for air circulation other than temperature deference and buoyancy force exerted by the chimney. Ideally, solar dryers are provided with narrow air inlets of about 0.05 m so as to ensure adequate contact of inlet air with the absorber plate for heating. This however comes with an increased drag force as a result of friction. To enhance air circulation while incorporating a reversed ab-

sorber to the system, a parallel flow heating system would be adopted. The design objective of the parallel flow solar air heater configuration is to optimize the heat transfer transportation in the solar air heater. The suspended-plate solar-energy air heaters have been reported to operate at higher efficiencies (up to 65% for the parallel flow type) than the bare-plate, front-pass or back-pass solar air heaters[20, 5] The system consists of a glass cover at the reversed absorber side and on top of a flat plate collector. Two black painted aluminum absorbers plates are used. The first absorber receives insolation from the glass cover above the flat plate section while the second is heated by the use of a cylindrical reflector. Air flows into the system through two ducts and is driven through the system by natural convection. As the air passes over the two absorbers, it gains thermal energy, leading to a hotter outlet air. This heated air is introduced to the heating chamber from beneath for the purpose of drying. When loaded, heat is transferred to the material to be dried leading to the extraction of moisture and densification of process air. A chimney is incorporated to regulate the residency period of the process air and avoid overheating. The designed dryer is shown in the Figs. 1-2;

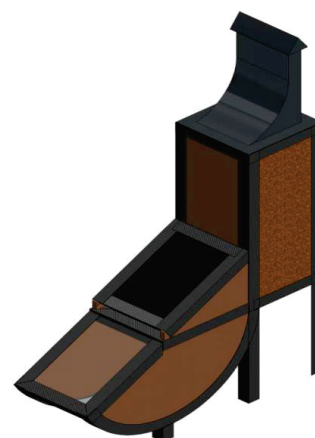


Fig.1: CAD design of the Dryer



Fig. 2: Constructed Prototype of the dryer

2.1.1. The heat collection unit.

This is made up of a flat plate collector side and a reversed absorber side joined to form a parallel flow air heating channel. In whole, the unit consists of a reflecting arc, two absorber plates and glazing glasses on both the flat plate and reversed absorber side. The reflector part of the collector directly receives incident rays of the sun and transmits such to the reversed side of the absorber. Some researchers achieve the reflecting arc by setting up five equal flat surfaces in a polygonal arrangement and covering them all with an aluminum foil[21, 19]. However, the most important consideration in designing the reflector is that the area of its aperture has to be equal to the area of the absorber[21-22]. In the current design, a flexible ply board was used to form the reflecting arc and then coated with a light, reflective aluminum sheet.

A major consideration for the selection of an absorber is the cost of such material and its local availability since the best heat absorb-

ing materials are quite expensive, a trade off has to be made between cost and effectiveness. A suitable material for use as absorber plate should have high absorptance of incident radiation, low emissivity, good thermal conductivity, thermal stability under temperature regimes encountered during operation and must be durable and affordable.

The collecting unit has to be at an optimal angle, which is a function of the local latitude. The ideal collector slope at solar noon of a particular day for a chosen site can be computed from the following[23].

$$\beta = (\phi - \delta) \quad (1)$$

Where the declination angle δ is given by

$$\delta = 2.45 \sin \left(360 \frac{284+n}{365} \right)$$

n is the Julian number .

β is the collector slope from the horizontal

θ is the Latitude of location (positive – north of equator and negative – south of equator)

2.1.2. Drying chamber

This compartment is made up of a wooden rectangular enclosure partitioned horizontally by trays. The choice of wood eliminates the need for further insulation and makes the dryer more affordable. The trays are made of metallic frame covered beneath with wire gauze. These trays are placed well above the dryer's air inlet to ensure that only sufficiently heated air makes it to the tray for drying. The trays are also painted black to enhance heat absorption from the process air and consequent transmission to the materials being dried.

2.1.3. Chimney

Air flow rate is crucial to the overall performance of the system. The higher the mass flow rate, the higher the efficiency of the collectors. Low mass flow rate on the other hand reduces the thermal performance of the system. The natural ventilation due to chimney effect is given by the following equation[24];

$$C_2 = \sqrt{\frac{gH \frac{T_{in} - T_{amb}}{T_{in}}}{1 + \frac{A_2^2}{A_1^2}}} \quad (2)$$

C_2 Air velocity in the chimney

T_{in} is the collector inlet temperature

T_{amb} is the ambient temperature

A_1 area of dryers inlet orifice

A_2 chimney's outlet area

H is the horizontal distance between dryer's inlet orifice and the chimney's outlet orifice.

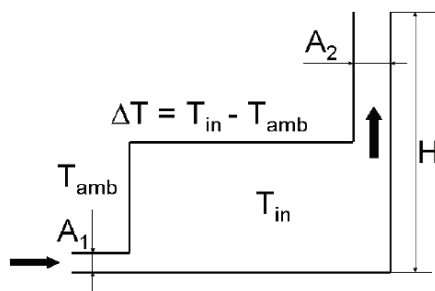


Fig. 3: Schematic representation of the dryer showing important parameters

Table 1:A summary of the physical properties of the dryer. Dimensions in cm

Part	Num-ber	Material	Dimension
Glazing sheets	2	Transpar-ent glass	50×50×0.3
Ab-sorber plates	2	Black painted aluminum sheet	45×50
Drying chamber trays	--	Ply board	3cm Thick
Chimney	1	Mild steel	50×46×6
Reflec-tive sur-face	1	Aluminum sheet	50×120
Overall frame	--	Mild steel angle bars	Varied

2.2. Instantaneous Efficiency of the Dryer

The instantaneous efficiency of the dryer is evaluated using the following equation:

$$\eta = \frac{\dot{m} C_p (T_{out} - T_{in})}{A_c G} \quad (3)$$

Where:

M = Mass flow rate of the working fluid (kg/s)

C_p = Specific heat capacity of the fluid (J/kg·°C)

T_{out} = Outlet temperature of the fluid (°C)

T_{in} = Inlet temperature of the fluid (°C)

A_c = Collector aperture area (m²)

G = Solar radiation (W/m²)

The instantaneous thermal efficiency (η) of a solar collector is influenced by the variation in solar radiation and the temperature difference between the fluid and the environment.

2.3. Instrumentation of Experiments

The experiments to determine the performance of the dryer was carried out at the National Centre for energy research and development. The Centre is located in Nsukka, (6.8429° N, 7.3733° E) Enugu state, South east Nigeria. The details of the instruments used and what data was collected with then is given below.

Table 2: The instruments used and their specifications

<i>Instru- ment</i>	<i>Model</i>	<i>Varia- ble</i>	<i>Unit</i>	<i>Accuracy</i>
<i>Digital tempera- ture me- ter (K- thermo- couple)</i>	Lutron MTM- 380SD	Tem- pera- ture	°C	±0.5% +0.5 °C
<i>Solarime- ter</i>	Lutron SPM- 1116SD	Irradi- ance	W/ m ²	±10 or ±5%
<i>Hot wire anemom- eter</i>	8903	Ambi- ent air- speed	m/s	±3%±0.1
<i>Hot wire anemom- eter</i>	8903	Ambi- ent air temp.	°C	±1.0 °C

2.4. DATA COLLECTION

A no load experiment was performed using the constructed dryer. The essence of this was to ascertain to what level the dryer was able to raise the temperature of process air, which in turn is an indication of how much heat would be available for drying materials. In this, the empty dryer was positioned to be south facing having the door tightly closed such that air enters and exits only through the collector inlet and the chimney respectively. K thermocouple wires were placed at various positions in the dryer as well as out-

side for ambient temperature data collection. The solarimeter was also placed at a plane parallel to the collector to record insolation data. Both the temperature meter and solarimeter were set to automatically collect data every 5 minutes.

3.RESULTS

The no load experiment was carried out on the 26th of march, 2024. From the graph of the ambient data for the day in Fig. 4, it is observed that there was clear sky the majority of the day as the insolation graph gave an evenly distributed dome like shape, peaking at the solar hour (12:15pm) at the maximum value of 982.6W/m². The ambient temperature was as well characteristic of the prevailing weather condition, ranging between 28°C and 38°C during the period of the experiment which spanned from 08:00am to 5:00pm.

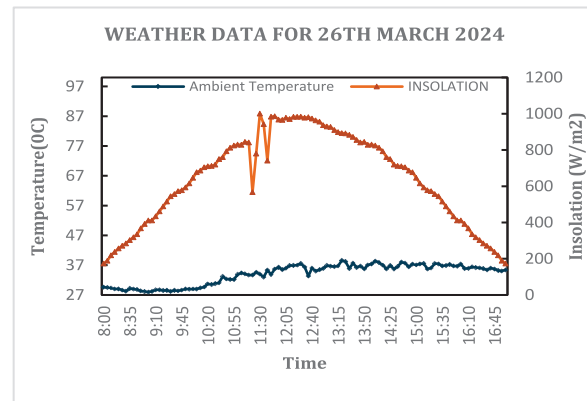


Fig. 4: Graph of Ambient temperature and Solar radiation on the 26th of march, 2024

The no-load temperature profiles of the various parts of the dryer is shown in Fig. 5. The collector inlet, collector outlet and drying chamber temperatures all started out being almost equal at the early hours of the day when insolation was below 400W/m². As more and more energy from the sun became available to the dryer, a significant tempera-

ture difference was observed between the collector inlet temperature and the drying chamber temperature with differences ranging as high as 6 – 10 °C at some points in the day, the highest being around solar noon.

There is a clear correlation between the collector's outlet temperature and the temperature within the drying chamber. Since no load was placed in the dryer, the difference between this temperature and that within the dryer especially during the dryer's peak hours of operation accounts for the thermal losses within the dryer. At 12:40pm this difference had a maximum value of 2°C. The losses could be attributed to the use of ply board alone for insulation to save costs.

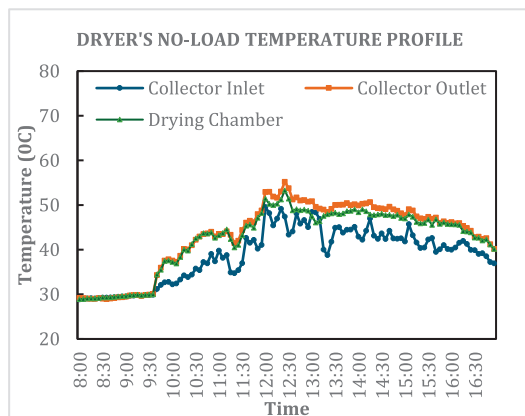


Fig. 5: Dryer's no-load temperature profile

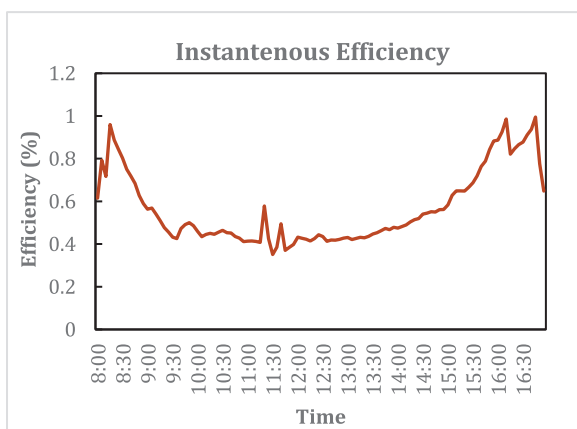


Fig. 6: Graph of instantaneous Efficiency of the dryer

From Fig. 6, the instantaneous efficiency of the dryer starts relatively high owing to the fact that there is minimal temperature difference between the ambient and the dryer's process fluid as seen in Fig. 5. At peak solar radiation, the collector's temperature rose significantly, causing a surge in heat losses through convection and radiation, therefore, the efficiency dropped to its lowest point during this period. In the evening hours, as solar radiation declines, heat losses reduce and temperature difference between the ambient and within the dryer declines as well, giving a similar efficiency values as observed in the early morning hours. This in effect

accounts for the U-shaped graph obtained in Fig. 6.

4. CONCLUSION

A passive solar dryer assisted with a reversed absorber was designed and tested. Results showed that the dryer was able to generate up to 10°C temperature difference between the ambient and the drying cabinet at peak solar hours. The 2°C temperature drop observed was attributed to the poor insulation achieved by the ply board walls, however, this ensured that the dryer's overall cost remained low. The instantaneous efficiency plot showed that the dryer obtained performances similar to existing solar thermal devices maintaining a base efficiency value of 37% at no load. This impressive performance testifies to the efficacy of the reversed absorber set up in boosting the performance of passive dryers while maintaining a low cost profile.

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DUAL-FUNCTION BIOMASS ROCKET STOVE

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Abstract: Energy for cooking is an inevitable demand for every house and food based businesses. Saving wood energy while cooking is important because it helps conserve natural resources, reduces deforestation, mitigates climate change, improves indoor air quality, saves money on fuel costs, and can significantly benefit communities that rely heavily on firewood for cooking. Energy conservation has been one of the utmost preferences in the utilization of energy from all sources. The daily increase in cost, availability and side effects of conventional cooking fossil fuels creates a large room and need for alternative fuel sources. The use of biomass (wood, charcoal etc.), just as it was the first source of fuel for heating activities appears to be the closest alternative. Moreover, challenges in operations and side effects accompanying the current practice in the use of biomass fuel for cooking and other heating purposes are constantly increasing. Typically, wood burning from the outer covering of the stove yielding soot, ashes and smoke make handling during operation very difficult. Although there are fair attempts to innovate suitable stoves to address these bottlenecks experienced with conventional stoves, a breakthrough is yet to be witnessed in terms of energy conservation, soot and smoke reduction while achieving cooking and/or heating using a single heat energy source. This work presents the design of a Dual-Function Biomass Rocket Stove aimed at energy efficiency and holistic eradication of these problems.

Key Words: Energy, Cooking, Biomass, Efficiency, Alternative, Dual

1. INTRODUCTION

Energy is necessary, and not only for driving economic development of a country, but also to secure all sustainable environmental conditions. About three (3) billion people around the globe are currently depending on solid fuels as source of energy, such as the wood biomass, charcoal, coal, agricultural residues and animal waste to meet their daily cooking and heating needs [5]. Wood fuel is the primary source of energy in the developing world for cooking. It is pertinent to establish mechanisms so as to make the combustion and transfer of heat generated from these fuels more efficient so as to reduce the fuel consumption and demand for wood. The large preference for wood as fuel is predicated upon the fact that apart from wood and coal the other primary non-re-

newable sources of energy such as petroleum, natural gas and liquefied natural gas are no longer easy to come-by in terms of cost and availability. The dependence on fuel wood by the rural dwellers of most developing countries including Nigeria is estimated to be about 100%, while about 70 million cubic meters was estimated as the annual fuel wood consumption [4].

Although, fine and ultrafine particulate matter emits during biomass combustion, and this has been a significant concern to both regulatory authorities and environmental scientists because of their effects on human health and the environment. Thus, emphasis is channeled on optimizing the performance of a biomass fuel/stove in order to reduce emissions and improve energy efficiency, to address all the problems associated with the

continuous use of biomass fuels in traditional cook stoves [5]. Design of cook stoves has significantly grown from being an art involving trial and error or iterative design principles to a more complex scientific and engineering exercise including the use of mathematical models such as finite element analysis and computational fluid dynamics [3]. Better performances were obtained on the improved stoves when compared to the average thermal efficiency for unimproved stoves [1,2]. Plate 1 is a biomass stove commonly referred to as the Kenya Ceramic Jiko (KCJ) is based on a metal cladding with a ceramic liner. Its current design was developed based on the Thai bucket stove, yet was unstable and overheats. The metal-clad version was developed by a women's community group, suggesting that the shape of an hourglass would be safer to use. In addition, less amount of vermiculite was added to the clay in order to regulate the cooking temperature, also preventing metal fatigue and reducing overheating. However, this type of conventional stove permits only a single heating activities at a time, and it is not energy conservative because, it does not utilize up to 2/3 of the heat energy generated during combustion due to the open top for easy heat escape which increases the degree of heat loss, whereby, the heat is released to the environment. Consequently, a single batch of the feedstock usually does not complete the cooking without refill, thus, more feed stocks will be required, and heating may start all over again, thus, prolonging the cooking or heating. Furthermore, when cooking is completed and there are still fuels left in the stove, the entire stove is to be lifted and turned over to evacuate the combusting fuels for extinguishing, and this most times result to accident, whereby the operator gets

burnt by either the heat of the stove when in contact or the clay used gets broken. Although, water is sometimes used for extinguishing the combusting fuels, but in the process, the environment gets littered with ashes and also, the clay cracks and weakens over time, thus, reduces its life span. In addition, the user may decide to leave the remaining fuel to burn off to ashes, which adds to the degree of wasting energy.



Plate 1. Kenya ceramic jiko
(Source: European Commission)

The stove shown in Plate 2 is a computer-aided drawing schematics of the stoves developed by [4]. According to his report, the stove is made from 25 L galvanized iron paint containers and iron tubes. Following the basic design of the biomass 'rocket stove' concept, with modifications in the shape of the fuel hopper, number of secondary air inlets, size of the combustion chamber, and the presence of a removable ash collector. Although, the biomass stove has an additional metal sleeve surrounding the primary com-

bustion chamber which preheats the primary oxidation air before being reintroduced into the combustion chamber, above the fuel bed, as secondary air. Furthermore, the gap between the outer surface of the metal sleeve and the stove body ensures that the outer surface of the stove reaches a maximum temperature of 40 °C during normal stove operation.

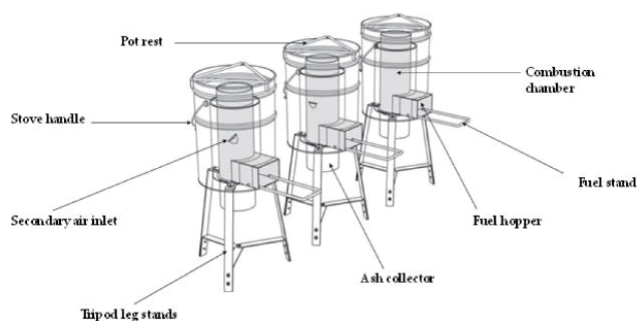


Plate 2. Biomass stove(Source: [5])

However, the temperature of the outer casing rises above the 40 °C of the normal stove operation when subjected to longer hours of operation, thus, increasing the chances of burn when the user touches it without protection. Similarly, only the heat that touches the bottom of the pot that heats up the pot, whereas, the rest go to the environment untapped, thus, increasing the cooking time in which more fuel will be added to the combustion zone. Likewise, more feed stocks are also required to complete cooking, as a result of the conventional open top heating application, and this makes the conventional cooking stoves poor energy conservative systems. In addition, the open top allows particles from the combustion chamber to fly out and enter into the food while making it unhealthy, and the smokes causing discomfort to the user, which is detrimental to their health, mostly, women and children. During operation, the ash pot cannot be

touched to evacuate ashes when it is filled, unless cooking or heating activities are stopped, so that temperature can get down to a safe level to prevent burn accidents. Thus, heating will start all over again when combustion is restored and this extends the cooking activities, with the fact that only a single pot can be heated at a time.

3.0 OBJECTIVES

The aim of this work is to design an energy efficient dual heating biomass stove which can be charged with wood, charcoal and biomass briquettes. The objectives are:

3.1 To design a Dual-Function Biomass Rocket Stove with the following characteristics:

- i. The stove can be used for as long as possible without raising the temperature of the external walls beyond safe level for the user to prevent accidents.
- ii. Heat generated from the combustion zone does not only heat the bottom of the pot but also heats the walls of the pot before leaving the environments of the pot, in order to expose more areas to heat thereby facilitating heating and/or cooking.
- iii. Heat generated first heats the first pot and then a second pot to ensure that a large percentage of heat generated is used before leaving the stove.
- iv. The exhaust gases are channeled properly to prevent particles of combustion from the user and from getting into the food during fuel refill, ash evacuation and fuel adjustments during cooking.

- v. Evacuation of ash from the ash pot does not halt cooking in any way.

3.2 Engineering drawings in isometric, orthographic and exploded views are shown in Figs. 1-6.

4.0 RESEARCH METHODOLOGY

Considering the ergonomic of the stove, marble slab was used as the desk of the stove, since it is not a good heat conductor. Likewise, the heating compartments are not directly connected to the walls of the stove enclosure, rather, they rest on a stand that is rooted on the bottom plate of the enclosure. Thus, the rate of heat transfer to the enclosure will be low due to large area to cover, which also increases the rate of heat diffusion by heat convection. In addition, to significantly low the heat transfer to the enclosure, the heated components were isolated with high heat resistance materials, such as the fiberglass.

The heat leaving the combustion zone is forced to move round the system so as to heat the walls of the pot. A pot skirt is provided to ensure that, as the heat generated travels up as an exhaust gas, it must touch the body of the pot, which increases the heated areas of the pot, and then forced downwards outside the pot skirt still trapped by the gas collector. The exhaust gas collector channels the gas to the chimney where they are released to the atmosphere without dropping particles into the food and preventing the user from direct inhalation.

Furthermore, in-between the exhausted gas collector and the pot skirt, a pipe known as boiling ring is rolled around the pot skirt in form of spring and making contact. The boiling ring will be heated by radiation and conduction from the exhaust gases that moves downwards, in order to heat the water in it. The top end of the boiling ring is connected to the top of the water pot, similarly, the bottom end of the boiling ring to the bottom of the water pot. The water in the second pot is heated by the boiling ring using thermo-syphon process, whereby the heated water in the boiling ring is replaced by a lesser temperature water by density difference. In this regard, the stove utilizes more than 3/4 of the energy in the fuel used during combustion, enabling cooking/frying and/or boiling to be achieved in a single batch of combustion operation. Thus, saving time, energy and resources for same purpose. Ashes drop directly under the fuel magazine and remain there unless when evacuated during maintenance. Likewise, ash evacuation can be done without interfering combustion because, there is an opening provided for airflow to support combustion and can be used to reduce ashes during operation.

5.0 RESULT

The isometric view of the Dual-Function Biomass Rocket Stove is shown in Figure 1, where two cooking chambers are provided. The left side is where combustion takes place and used for either cooking or frying of all sorts when necessary, while the right side is for heating water.

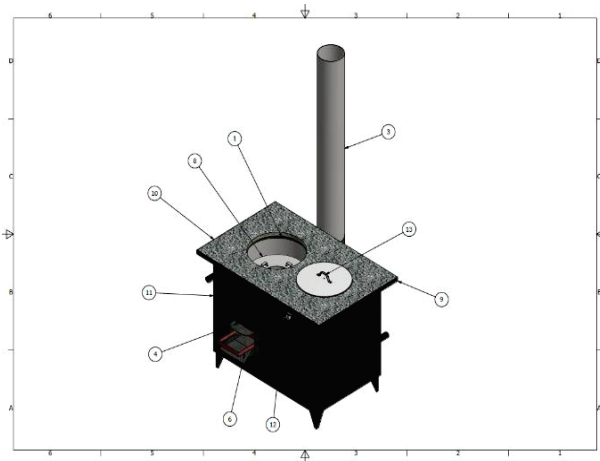


Fig. 1. Isometric view of the dual operated rocket stove

Fig. 2 shows the dimensions of the novel stove in an orthographic drawing. The minimum size of pot is 330mm diameter. This reveals the approximate space occupied by the stove within its application environment. The Chimney-2 (3) helps in channeling the exhaust gas to one direction as received from the Exhaust Gas Collector (5) shown in Figure 4. While feeding of fuel is carried out using the Fuel Magazine (6) which is capable of containing fuel for two (2) meals. The hot water pot is permanently fixed to both ends of the Boiling Ring (1), although, it has a Lid (13) that prevents dirt and other impurities.

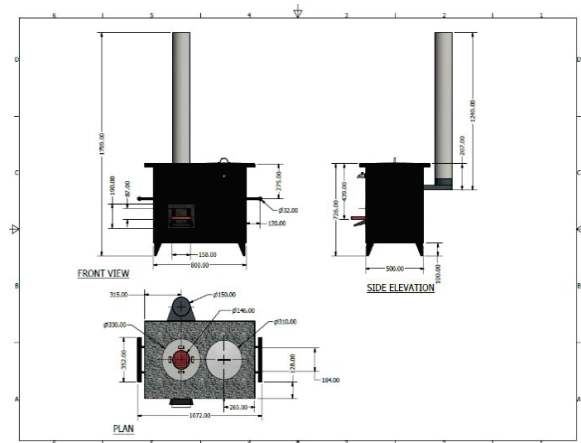


Fig. 2. Orthographic view of the dual-function biomass rocket stove

The Pot Skirt (8) has four legs stand which the pot seats when inserted. Thus, providing an adequate gap for exhaust gases and heat generated during combustion to pass through. The sectional view as shown in Fig. 3, shows that exhaust gases will pass between the Pot Skirt (8) and Exhaust Gas Collector (5), thus, heating the Boiling Ring (1). Likewise, Boiling Ring (1) is connected to the Hot Water Pot (7) so as, the water in the Hot Water Pot (7) is heated by the Boiling by thermo-syphon activity.

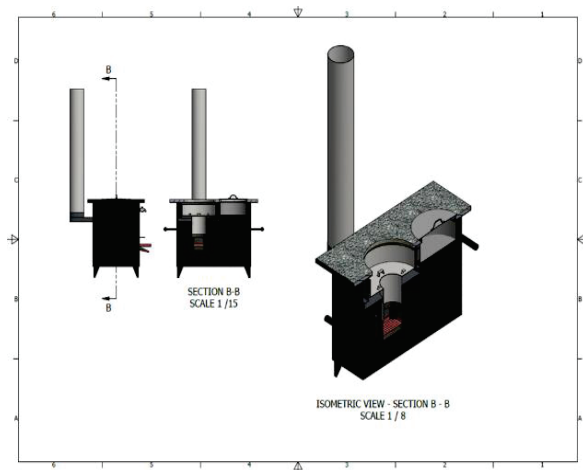


Fig. 3. Section view of the dual-function biomass rocket stove

As shown in Fig. 4, the components for the invention are Boiling Ring (1), Chimnry-1 (2), Chimney-2 (3), Combustion Zone and Ash Pot (4), Exhaust Gas Collector (5), Fuel Magazine (6), Hot-Water Pot (7), Pot Skirt (8), Top Cover – Marble Seat (9), Marble – Top Cover (10), Enclosure (11), Tap (12) and Lid (13).

The Enclosure (11) is made of mild steel and insulated with a fiber glass material which helps in reducing heat transfer that may be hazardous. Similarly, Marble – Top Cover (10), being a bad heat conductor, allows the user to touch or rest hands on it and use

some parts of the areas for other purposes due to its low temperature.

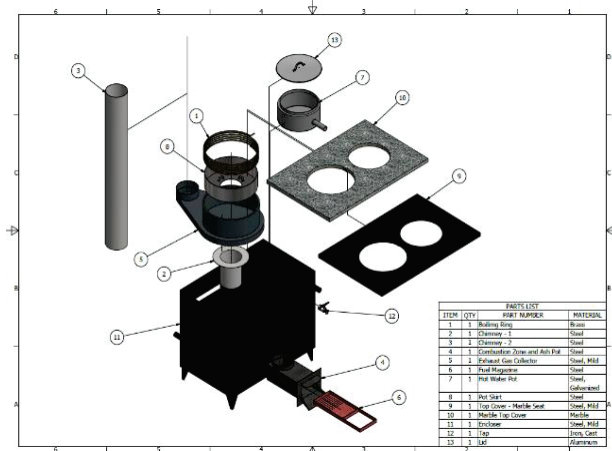


Fig. 4. Exploded View of the Dual-Function Biomass Rocket Stove

The Fuel Magazine (6) is fed with either charcoal, wood chips, pallets or briquettes as fuel for combustion. Which is then slide into the Combustion Zone and Ash Pot (4), where combustion takes place in a controlled manner and ashes generated are collected without littering the environment neither hindering cooking or combustion, and also, preventing particles going into the pot during cooking. As shown in Figure 6, the Chimney-1 (2) is directly attached and seated on the Combustion Zone and Ash Pot (4), which ensures the heat and exhausted gases generated are directed into the Pot Skirt (8). The Pot Skirt (8) is responsible for equal distribution of heat around the circumference of the pot. Thus, maximizing the heat transfer, unlike the conventional system of cooking, and reducing the time for cooking. The heat travels back into the Exhaust Gas Collector (5) through the walls of the Pot Skirt (8), which also reduces the heat losses from the body of the Pot Skirt (8). Thus, ensuring that a large percentage of heat reaching any part

of the pot is not shared nor underutilized before leaving the pot's zone. Exhaust gases are then channeled to the atmosphere through the Chimney-2 (3), which is connected to the Exhaust Gas Collector (5).

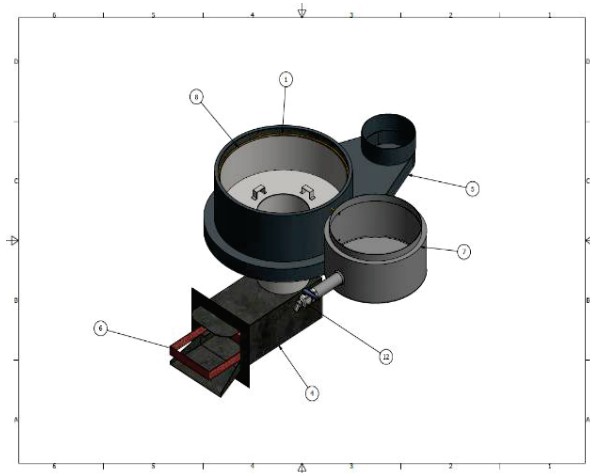


Fig. 5. Isometric view of heating systems of the dual-function biomass rocket stove

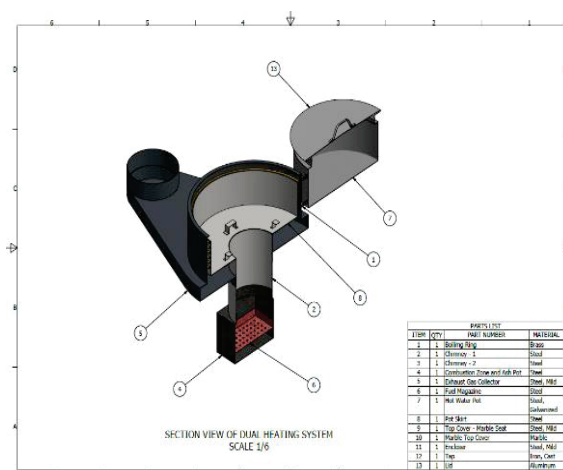


Fig. 6. Section view of heating mechanisms of dual-function biomass rocket stove

The Boiling Ring (1) is a copper pipe, rolled around the outside walls of the Pot Skirt (8) from up to down in a single line. The bottom end of the pipe is connected to the Hot-Water Pot (7) made of galvanized sheet metal, so as lower temperature water will flow in for heating, whereas the upper end of the pipe is connected to the upper side of the Hot-Water Pot (7) to discharge heated water into the Hot-Water Pot (7). The cycle continues until

the entire water in the Hot-Water Pot (7) heats up to approximately equal temperature. Hot water can be accessed directly from by opening the Hot-Water Pot (8) from the Lid (13) or from the Tap (12). Since sand and stones are bad heat conductors, a Marble Top Cover (10) was used as the desk of the stove, making it safe for user from burns due to excess heat caused by heat transfer.

Therefore, both cooking and boiling are achieved in a single batch of biomass fuel combustion in the stove.

6. CONCLUSION

A dual-function energy efficient biomass rocket stove which can be fired by wood,

charcoal and biomass briquettes have been designed. Unique components of the stove to ensure better utilization of energy include: Boiling Ring (1), Chimnry-1 (2), Chimney-2 (3), Combustion Zone and Ash Pot (4), Exhaust Gas Collector (5), Fuel Magazine (6), Hot-Water Pot (7), Pot Skirt (8), Top Cover – Marble Seat (9), Marble – Top Cover (10), Enclosure (11), Tap (12) and Lid (13). It is believed that the introduction of this novel technology shall enable efficient utilization of biomass fuel for cooking.

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FUTURE PERSPECTIVES OF COMPRESSED NATURAL GAS RESEARCH IN NIGERIA

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Abstract: Compressed Natural Gas (CNG) has gained increasing attention as a sustainable alternative to conventional fossil fuels. Challenges and bottlenecks associated with the widespread adoption of CNG in Nigeria such as infrastructure limitations, high initial costs, and issues surrounding gas leakage, which can offset environmental benefits are highlighted. In addressing these challenges, recent research highlights solutions such as the development of high-capacity storage systems, digital monitoring for leak detection, and cost-effective refuelling infrastructure. Toward finding a comprehensive roadmap for stakeholders to leverage the potential of CNG as a key contributor to sustainable energy solutions, this review also explores current trends and future perspectives of CNG research, emphasizing its potential to mitigate environmental concerns, enhance energy security, and foster sustainable development. Innovations in lightweight composite materials for CNG cylinders, integration of advanced electronic control systems, and incorporation of renewable biomethane and hybrid CNG-electric systems, are presented as pathways for enhancing the sustainability of CNG technologies. Future perspectives focus on the integration of CNG with emerging energy paradigms, including hydrogen-blended CNG (H-CNG) and its role in the transition to a low-carbon economy. The importance of multidisciplinary collaborations and policy support in driving innovations and scaling the adoption of CNG technologies globally is emphasized.

Keywords: Compressed natural gas, Current trends, Research and development, Alternative fuel, Sustainability

1. INTRODUCTION

Several compelling reasons, including energy security, environmental concerns, and cost efficiency, have necessitated the need to seek alternative fuels that will replace or augment fossil fuels [1-3]. Commonly explored alternative fuels include renewable fuels such as

gaseous fuels and electricity. Commonly explored alternative fuels—developed to reduce dependence on fossil fuels and minimize environmental impact—include gaseous fuels such as liquefied petroleum gas (LPG), compressed natural gas (CNG), , hydrogen gas, propane; alcohols such as ethanol, methanol, butanol; vegetable oils, and waste-derived oils [4]. Other renewable fuels that are also explored include biofuels, biogas, biomethane, renewable hydrogen, as well as e-fuels such as e-kerosene, and ammonia [5].

Natural gas (NG) is a naturally occurring mixture of hydrocarbons that is recognized as the most environment-friendly fossil fuel utilized mostly as compressed natural gas (CNG) and as liquefied natural gas (LNG)[6]. CNG is a NG comprising mostly methane pressurized at 250 bar to less than a hundredth of its original volume. Other components of CNG include ethane, propane, and butane[7]. CNG as a clean and cheap fossil fuel is utilized in households, plants, and factories [3] as a fuel for power generation [8], cosmetics production, food processing, and transportation fuel [7, 9]. CNG has experienced robust growth as the world moves towards green energy solutions [10]. Thus, CNG has become a popular automotive fuel in several countries over the past decade. The growth is propelled by increased environmental awareness and more stringent emission regulations. Also, the cost-efficiency and availability of CNG have become key drivers for its adoption, especially in de-

veloping countries. Hence, to cut costs, reduce carbon footprints, and comply with emission standards, fleet operators and public transportation agencies have begun to adopt CNG as a sustainable fuel option which has played a critical role in the growth of the CNG industry[9, 11, 12]. As with other industries, the rapid expansion of the CNG industry through its adoption in various sectors is occurring with emerging opportunities and accompanying challenges. As governments, laboratories, and other research institutions tighten their research budgets and sponsorships, there is a need for more focused research work that aims to solve global challenges and find solutions to pressing issues. CNG research is advancing rapidly, with research focusing on several key areas to enhance its viability as a cleaner alternative fuel.

This paper aims to guide policymakers and other stakeholders in the fast-evolving field of CNG research toward leveraging the potential of CNG as a key contributor to sustainable energy solutions. The current challenges, research trends, and future perspectives of CNG are explored with emphasis on its potential to mitigate environmental concerns, enhance energy security, and foster sustainable development across the globe.

2 CONTEXT

2.1. Challenges and Limitations of CNG Adoption

Despite its promising attributes, several challenges persist in the use of CNG as an alternative fuel. Mamon 2024 [11] has identified infrastructural development, supply, safety, and technical competency (Fig. 1) as some of the areas that pose both opportunities and challenges for the adoption of CNG as a transportation fuel



Fig. 7 Areas of challenges towards the adoption of CNG as a transportation fuel [11]

Onibiyo 2024 [13] identified several factors that constrain the adoption of CNG as a transportation fuel in Nigeria which include inadequate refuelling infrastructure in rural and remote areas, absence of locally fabricated retrofitting kits, retrofitting costs, regulatory and policy challenges, low Public perception and awareness. Some of the most common bottlenecks towards proper adoption of CNG are highlighted below.

2.1.1 Infrastructure Gaps

Inadequate refuelling stations and lack of customized retrofitting kits is a challenge in the wide-scale adoption of CNG as transportation costs in rural and remote areas. According to the Presidential CNG Initiative (Pi-CNG)[14], there are only 160 registered retrofitting centres across Nigeria which is drastically inadequate compared to the population and the estimated number of vehicles in the country.

2.1.2 Competition with Emerging Fuels

Renewable energy sources, hydrogen, and electric vehicles present stiff competition to CNG in the long-term sustainable energy landscape. However, in Nigeria and other developing countries, while the application of

renewable energy sources (RES) such as solar and wind have reached commendable stages in many sectors, the application of RES in the mass transportation sector is still lacking [15]. Nigeria has a formidable electric vehicle initiative with the market steadily improving, and sustainable development of the initiative is affected by inadequate charging stations and inadequate electricity supply [16]. Amoo and Fagbenle, 2014 [17] predicted that up to the year 2030, even when adopted as a transportation fuel, hydrogen's contribution to energy production and demand will be very minor due to its slow turnover rate. Hence, aggressive research on CNG and its advantages over other emerging fuels should be intensified.

2.1.3 High initial costs

Despite the long-term benefits of CNG-run vehicles which include the 40 % reduction in fuel costs [18], the high initial costs of the vehicle retrofitting process are still on the high side. Even though the Federal Government has subsidized the costs and made the conversion of commercial vehicles free of all charges [19], the absence of adequate conversion and refuelling centres has caused long delays for vehicle owners willing to follow the government's initiative. Okediran [20, 21] reported that the cost of retrofitting vehicles was determined by the number of cylinders of the vehicle, the location, and the conversion center used. The conversion costs for a four-cylinder vehicle were in the range of ₦ 0.73 to ₦1.3m while for a six-cylinder vehicle, it was about ₦1.8m. The high initial costs of CNG vehicle conversions are a challenge that researchers, policymakers, and other stakeholders in the industry need to address to encourage the adoption of gas as a transportation fuel.

2.1.4 Safety Concerns

While research advancements have enhanced CNG safety, the high-pressure storage of the gas necessitates continuous improvements in its safety protocols. A recent report of a CNG vehicle explosion at a filling station in Benin City [22] and the purported plan of Malaysia to ban the use of CNG vehicles in 2025 [23] has raised CNG safety concerns among Nigerians. Addressing safety issues and concerns associated with the use of CNG in vehicles is key to ensuring the successful and sustainable adoption of this technology in Nigeria. By enforcing stringent safety standards and regulations, training and certifying technicians, and intensive public awareness, Nigeria can improve the acceptance and adoption of the technology.

2.2 PROFFERED SOLUTIONS TO CHALLENGES

2.2.1 High Capacity Storage tanks

CNG affordability and abundance make it a competitive transport fuel option for both developed and emerging economies. However, its transportation to remote areas and storage in large volumes in such areas has posed some challenges. Research has made notable progress in enhancing fuel storage, energy efficiency, and engine compatibility. Breakthroughs in material sciences, such as lightweight composite cylinders, have improved storage capacity and safety standards. Similarly, advancements in engine technologies have optimized fuel efficiency and reduced fuel consumption and subsequent emissions. An increase in refuelling stations and CNG distribution networks is key to improving the adoption of gas. More research needs to be tilted in that direction.

2.2.2 Cost-effective Refuelling Infrastructure

To improve the performance of CNG refuelling stations, Farzaneh-Gord et al. [24] identified three main factors which include filling time, filling mass, and the reservoir tank utilization ratio. Cost-effective refuelling stations can enhance service delivery and lower costs. Much research effort should be geared toward a more robust design and optimization of fuelling stations, and the design of smart systems that can dispense, monitor, and manage CNG infrastructure safely and economically.

2.2.3 Digital Monitoring for Leak Detection

One of the most critical safety concerns of CNG is the timely detection of leaks, as even minor leaks can escalate into significant safety and environmental hazards. Digital monitoring systems for CNG leak detection hinged on IoT-based smart gas leakage represent a transformative solution that combines advanced sensor technology, real-time data analytics, and automated alerts to enhance safety, efficiency, and environmental protection. Babu et al., [25] opined that the possibility of providing early, real-time, and swift alert mechanisms has prompted the integration of the Internet of Things (IoT) into gas leakage detection systems. Traditional methods of leak detection, such as manual inspections or basic sensor systems, are often insufficient to ensure rapid and precise CNG leak detection. Manual leak inspections are time-consuming and prone to human error, while conventional sensors might lack the sensitivity to detect minute leaks or may not provide continuous monitoring. These limitations can lead to delayed responses, increasing the risk of accidents and costly losses. Digital monitoring systems overcome these challenges by providing continuous surveillance, instant alerts, and detailed diagnostics. Digital monitoring for CNG leak detection represents a vital innovation in

energy safety and environmental sustainability. By leveraging advanced technologies, such systems ensure rapid detection, accurate diagnostics, and proactive mitigation of leaks, safeguarding both lives and the environment. As technology evolves, digital monitoring will become an indispensable component of modern CNG infrastructure.

2.3 EMERGING RESEARCH OPPORTUNITIES ON CNG

As the global focus shifts toward achieving net-zero emissions and enhancing energy efficiency, the field of CNG presents a wealth of research opportunities. These include advancements in storage and compression technologies, optimizing combustion processes for greater efficiency, integrating CNG with renewable energy systems, and exploring innovative materials for CNG storage. By addressing these areas, researchers can help unlock CNG's full potential, contributing to a more sustainable and resilient energy future. Fig. 2 shows some of the major areas that policymakers and researchers need to focus on to enhance CNG utilization.

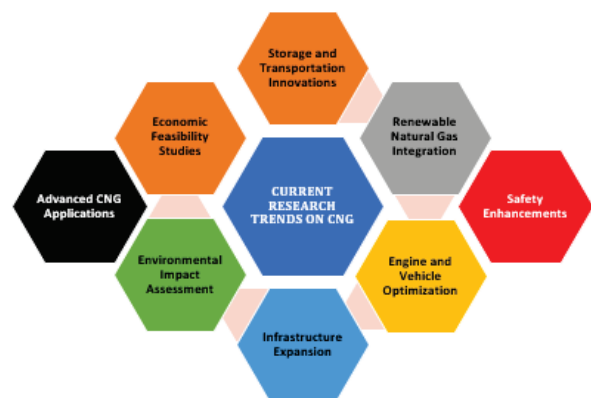


Fig. 2 Current trending areas on CNG research

2.3.1. Storage and Transportation Innovations

Developing advanced materials and methods to improve the efficiency and safety of

CNG storage and transport, such as lightweight composite tanks and adsorption technologies. Some viable topics in this area include:

- Advanced Materials for High-Pressure CNG Storage Tanks: Enhancing Safety and Efficiency.
- Adsorption-Based Storage Systems for Compact and Energy-Efficient CNG Transport.
- Comparative Analysis of CNG Cylinder Designs for Improved Durability and Lightweight Applications.

2.3.2 Renewable Natural Gas Integration

Exploring the production and utilization of renewable natural gas (RNG) from organic waste sources to blend with or replace conventional CNG, enhancing sustainability. Topics worth exploring in this area include:

- Integration of Renewable Natural Gas (RNG) into CNG Supply Chains: Challenges and Opportunities.
- Exploring Biogas Upgrading Technologies for High-Quality CNG Production.
- Assessing the Potential of Solar-Powered CNG Refueling Stations.

2.3.3 Engine and Vehicle Optimization

Enhancing engine designs and vehicle systems to maximize performance and fuel efficiency when using CNG, including dual-fuel systems and retrofitting technologies. Researchers interested in this area may consider:

- Optimization of Dual-Fuel CNG-Diesel Engines for Heavy-Duty Vehicles.
- Performance Evaluation of Retrofits for Gasoline Engines to CNG Operation.

- Advanced Ignition Systems for Improving the Efficiency of CNG Combustion Engines.

2.3.4 Infrastructure Expansion

Researching cost-effective solutions to expand CNG refuelling infrastructure, aiming to increase accessibility and convenience for consumers and commercial fleets. Topical issues that may be explored in this area may include topics like:

- Design and Optimization of CNG Refueling Stations for High-Demand Urban Areas.
- Assessing the Challenges and Opportunities for Expanding CNG Distribution Networks.
- Smart Systems for Monitoring and Managing CNG Infrastructure Safety.

2.3.5 Environmental Impact Assessment

This area requires conducting comprehensive studies to evaluate and mitigate the environmental impacts of CNG production and usage, ensuring alignment with sustainability goals. Examples of topics that can be explored in this area include:

- Evaluating the Role of CNG in Reducing Greenhouse Gas Emissions in Urban Transportation.
- Air Quality and Greenhouse Gas Emissions: Assessing the Role of CNG in Urban Environments
- Impact of CNG on Communities around Tank Farms and Dispense Stations.
- Lifecycle Environmental Impact Assessment of CNG vs. Traditional Fossil Fuels.

2.3.6 Economic Feasibility Studies

Analyzing market trends and economic factors to assess the competitiveness of CNG in comparison to other fuels, considering fac-

tors like pricing, availability, and policy incentives. Stakeholders in the CNG value chain may explore topics such as:

- **Life Cycle Analysis of CNG as a Cleaner Alternative to Diesel and Gasoline.**
- **Economic Feasibility of Large-Scale Adoption of CNG in Developing Countries.**
- **Cost-benefit analysis of CNG Infrastructure Development for Urban Transportation Systems.**

2.3.7 Safety Enhancements

Improving safety protocols and technologies related to CNG handling, storage, and usage to address potential risks and enhance public confidence. The following research trends aim to address existing challenges and promote the adoption of CNG as a viable, cleaner alternative in the global energy landscape:

- **Risk Assessment Models for CNG Storage and Handling in Urban Environments.**
- **Development of Advanced Leak Detection Systems for CNG Distribution Networks.**
- **Standardizing CNG Safety Protocols for Automotive and Industrial Applications.**

2.3.8 Advanced Applications

More advanced applications of CNG need to be explored toward obtaining hybrid applications that will ensure the sustainability of CNG as a transportation fuel.

- **Investigating the Role of CNG in Hybrid Energy Systems for Sustainable Transport.**
- **CNG as a Transition Fuel for Hydrogen-Powered Vehicles: A Comparative Study.**
- **Innovative Storage Solutions for Advanced CNG Applications.**

- **Biomethane Production:** The production of biomethane from organic waste for CNG applications aligns with circular economy principles, further enhancing its environmental credentials.
- **Artificial Intelligence (AI) and Data Analytics:** Employing AI and big data can optimize CNG production, distribution, and consumption patterns, ensuring sustainability and cost-effectiveness.

3 CONCLUSIONS

Compressed Natural Gas (CNG) has emerged as a pivotal alternative fuel in the global transition towards sustainable energy systems. This review highlights the multifaceted advancements and challenges within the domain of CNG, encapsulating its potential as a cleaner and cost-effective energy source compared to conventional fossil fuels. CNG has demonstrated a significant reduction in greenhouse gas emissions and particulate matter, positioning it as a viable solution for decarbonizing transportation and industrial sectors. Governments and private stakeholders have contributed significantly to infrastructure expansion, particularly in regions with high potential for natural gas reserves. CNG holds immense potential to contribute to a sustainable energy future, particularly in the transition phase towards a carbon-neutral economy. For CNG to achieve widespread adoption and efficacy, research must prioritize scalability, integration with emerging technologies, and safety enhancements. Continued collaboration between researchers, policymakers, and industry leaders will play a pivotal role in realizing the full potential of CNG as a cornerstone of clean energy solutions.

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2.4 FUTURE PERSPECTIVES

The future trajectory of CNG research and application should be shaped by innovations and strategic policy support:

- **Policy and Market Incentives:** Strengthened policies, subsidies, and public-private partnerships are critical to accelerating the adoption of CNG technologies and infrastructure expansion.
 - **Multidisciplinary Collaborations** The synergy between researchers from various fields is key in the presentation.
 - **Hybrid Systems:** The integration of CNG with hybrid and electric powertrain systems offers promising avenues for improving energy efficiency and reducing carbon footprints.
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THE EFFECT OF OIL-TO-METHANOL RATIO ON THE YIELD AND QUALITY OF BIODIESEL PRODUCED FROM WASTE FRYING OIL USING COPPER OXIDE NANOPARTICLES CATALYST

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Abstract: (1) Background: There is an urgent need to mitigate the environmental impact of fossil fuels and reduce global carbon emissions. Biodiesel is a renewable alternative energy resource to petro-diesel. However, the conventional transesterification process for biodiesel production uses basic hydroxide catalysts (eg, NaOH, KOH) which are toxic, not recoverable, and cannot be recycled. The hydroxides also form soap with waste frying oil (WFO) due to high free fatty acid content. Using non-soap-forming catalysts such as CuO-NPs for transesterification of WFO might improve yield and reaction time. In this work, CuO-NPs catalyst is utilized to convert waste frying oil to biodiesel and investigate the effect of the oil-to-methanol ratio on the biodiesel yield and fuel quality. **(2) Methods:** CuO-NPs were synthesized via a bottom-up approach using a precipitation method involving copper chloride dihydrate and copper acetate purchased from Merck. The NPs were characterized with X-ray diffraction (XRD), and Fourier-transform infrared spectroscopy (FT-IR). Batch transesterification of WFO was carried out at 1:1, 1:2, 1:4, 1:6, 1:8, 1:10, and 1:12 oil-to-methanol ratios. **(3) Results:** The results indicate that biodiesel yield increases with the oil-to-methanol ratio, reaching a maximum yield of 75% at a 1:8 oil-to-methanol ratio. Interestingly, the fuel properties of biodiesel fuel characteristics, including the kinematic viscosity (mm^2/s), density (0.82 g/cm^3), Iodine value ($50.2 \text{ g iodine/100 g Fat}$), and cetane number (82.5) are within the ASTM D6751 standards. **(4) Conclusions:** The findings imply that CuO-NPs can be a good replacement for basic hydroxide in the transesterification of WFO for biodiesel production.

Key Words: Biodiesel, CuO-NPs, Transesterification, Waste frying oil

1. INTRODUCTION

The pursuit of sustainable and renewable energy sources has garnered significant attention in recent years, driven by the urgent need to mitigate the environmental impact of fossil fuels and reduce global carbon emissions. Biodiesel, an alkyl ester derived from renewable biological sources such as vegetable oils and animal fats, is a promising alternative to conventional diesel fuel due to its biodegradability, lower toxicity, and reduced greenhouse gas emissions [1, 2]. However, the traditional production processes for biodiesel, primarily involving transesterification reactions, face several challenges, including high energy consumption, long reac-

tion times, and the need for substantial amounts of catalysts [3]. Applying nanoparticles as catalysts in biodiesel production will address these limitations and enhance the process's efficiency and sustainability.

Nanoparticles are particles with dimensions of 1 to 100 nanometers. Due to their high surface area-to-volume ratio and quantum size effects, they exhibit unique physical and chemical properties distinct from their bulk counterparts [4]. These characteristics make nanoparticles highly effective as catalysts, providing more active sites for chemical reactions and facilitating improved interaction with reactant molecules [5].

The use of nano-sized catalysts in biodiesel production via transesterification can significantly accelerate the process reaction, reduce the amount of catalyst required, and enable the use of lower-quality feedstock, thereby enhancing the overall efficiency and cost-effectiveness of the process [6, 7]. Furthermore, nanoparticles, are in solid forms making them easy to be recovered and re-used [8-9], unlike the homogenous catalysts, NaOH and KOH which are lost with each batch reaction. Additionally, the environmental benefits of using nanoparticles as catalysts are substantial, as they contribute to cleaner production processes with fewer by-products and lower energy requirements [10].

Nanoparticles catalyze biodiesel production and improve the fuel's general properties and engine performance. For instance, Karthikeyan *et al.* [11] reported that certain nanoparticles can enhance biodiesel's oxidative stability, combustion efficiency, and emission characteristics, making it a more viable and competitive alternative to petrodiesel [12]. Moreover, the nanoparticles of desired characteristics can be engineered at the synthesis stage by composition, size, and shape control, which offers opportunities to optimize biodiesel production processes and to develop new formulations with superior performance [13].

Although there are various metal oxide nanoparticles, transitional metal oxides including CuO are highly active and recyclable [14], and may lead to high biodiesel yield and reduction in transesterification time. In their study, Sulieman *et al.* [15] combined three transition metal oxides (CuO, NiO, and ZnO) to modify the CaO catalyst for improved biodiesel production from waste cooking oil.

Studies show the time reduction during transesterification with nanoparticles as well as biodiesel yield and characteristics

varied widely due to the influence of a range of factors, including the characteristics of the NPs and the oil, methanol-to-oil ratio, temperature, and catalyst loading [16]. Understanding the variability provides insight to optimize biodiesel yield and reduce reaction time. Cooking and frying oil in Nigeria are from various sources underscoring the need to investigate the transesterification of WFO for optimal biodiesel production.

Presently, biodiesel feedstock is mainly edible oil and accounts for over 70% of the cost of biodiesel production, making biodiesel 70 to 130% costlier than petrodiesel [17-18]. Non-edible and waste frying oils can be a cheaper alternative to edible oils, and applying nanoparticles will facilitate the development of a protocol for low-cost biodiesel production in Nigeria.

2. AIM OF THE STUDY

The work aims to produce biodiesel using waste frying oil, methanol, and CuO Nanoparticles.

Specific objectives are as follows:

- i. To synthesize and characterize CuO-NPs.
- ii. To obtain and characterize the waste frying oil.
- iii. To apply the CuO-NPs as catalysts for the transesterification of waste frying oil.
- iv. To characterize the biodiesel produced.
- v. To determine the effect of the oil-to-methanol ratio on biodiesel yield.

3. MATERIALS AND METHOD

3.1. Chemicals and reagents

The chemical reagents include methanol, sodium hydroxide, (NaOH), glacial acetic acid (CH₃COOH), and, Copper chloride dehydrate (CuCl₂ · 2H₂O), acetone, sulfuric acid, hydrochloric acid, Isopropyl alcohol, potassium hydroxide, ethanol, chloroform, potassium iodide, sodium thiosulphate, starch indicator, phenolphthalein, Wij's reagent, and ethanolic potassium hydroxide were analytical grade, purchased from Merck and used as received.

3.2. Collection and determination of free fatty acid content of waste frying oil

WFO were collected from three restaurants in Nsukka and blended. The oil was filtered to remove food particles and heated at 110 °C in an oven for about half an hour to remove water. The physicochemical properties of WFO including density, ash content, acid value, kinematic viscosity, and molecular weight and saponification value were estimated using standard procedures [19]. The free fatty acid (FFA) content of WFO was determined by measuring 1.03g of waste frying oil into a 250ml beaker, 10ml of isopropyl alcohol was added and 3 drops of phenolphthalein indicator was added to the solution and then titrated against 0.1M of KOH. This process was repeated thrice to get the average titre value.

$$\text{Acid Value} \left(\frac{\text{mg}}{\text{g}} \right) = \frac{MW_{\text{KOH}} \times C_{\text{KOH}} \times V_{\text{KOH}}}{\text{Mass of oil}} \quad (1)$$

$$\text{Free Fatty acid (\%)} = \frac{\text{Acid value}}{2} \quad (2)$$

3.3. Pretreatment of the waste frying oil

11.25g of methanol and 0.30g of H₂SO₄ were added to 500g of WFO, stirred for 1hr at 60°C. Then 250ml of warm distilled water was added to aid the separation of impurities from the oil. The mixture was transferred into a separating funnel and stood for 1 hour. The oil was washed with excess methanol to dissolve any impurities, after which the FFA value was determined. The process was repeated twice to reduce the FFA content to less than 2.5%.

3.4. Synthesis of CuO nanoparticles

The CuO nanoparticles were prepared by sol-gel method according to Prasad *et al.* [20], by precipitating copper salt alkaline solution using copper chloride dehydrate salt precursor. 5.4 g of CuCl₂·2H₂O was added to 100 mL of distilled water in a 250 mL beaker on a magnetic heating plate. The solution was stirred with a magnetic stirrer on a hot plate at 80 °C. This was followed by the drop-wise addition of 2 M NaOH to the solution with continuous stirring until the pH was 7.5 when the solution became brownish-black due to the precipitation of CuO nanoparticles. The mixture was maintained at 80 °C with stirring for 2h, after which it was centrifuged at 5000 rpm, allowed to stand for 30 minutes, and washed with distilled water. The dried CuO-NPs were annealed at 350 °C. The as-prepared CuO-NPs were crushed in a mortar characterization.

3.5 Characterization of CuO nanoparticles

The CuO-NPs were crushed were characterized using XRD, UV-Vis, and FTIR. The XRD was used to measure the crystal structure and size on a diffractometer with Ni-filtered CuKα radiation at λ=0.154 nm in the range of 2 theta 5–50°. The XRD results were ana-

lyzed with the origin software and the average crystal size of the catalyst was determined using the Debye Scherrer equation [21].

3.6. Transesterification of the pretreated WFO with CuO nanoparticles

The transesterification reaction was performed in a 500mL beaker using a magnetic stirrer with a heating and temperature control mechanism. The catalyst loading of 1% oil weight and temperature of 60 °C for transesterification were selected based on the literature [22], to avoid reduced conversion of the oil, given that transesterification with methanol at temperatures higher than the boiling point (64.7 °C) lowers biodiesel yield due to methanol boiling off [23]. About 5g of CuO-NPs was weighed and separately added to 200 mL methanol and stirred with a magnetic stirrer for 30 minutes. For a 1:1 oil-to-methanol ratio, 50 ml of WFO was weighed and preheated. Afterward, the methoxide and the preheated oil were mixed in the beaker and stirred for 2 hours at 60°C with a magnetic stirrer. The mixture was transferred into a separating funnel and stood for 1 hour. The glycerol settled down to the lower part of the separating funnel. To investigate the effect of the oil-to-methanol ratio on biodiesel production, the experiment was repeated for various oil-to-methanol ratios.

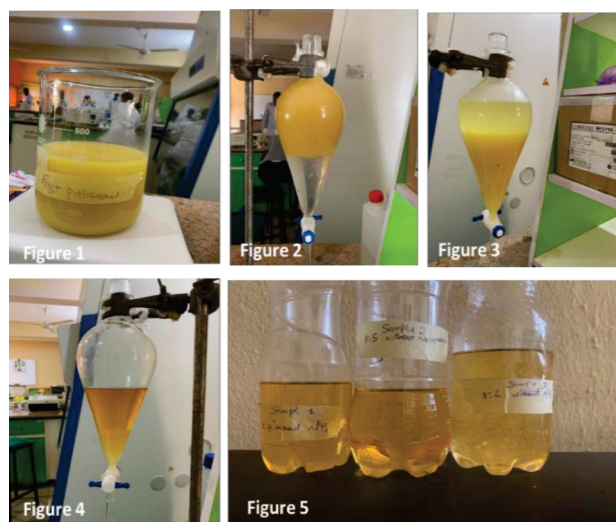


Fig. 1: Pretreatment of WFO, **Fig. 2:** Pretreated oil with washing water. **Fig. 3:** Pretreated oil with excess methanol. **Fig. 4:** Biodiesel with glycerol. **Fig. 5:** Biodiesel

Biodiesel yield(%)=

$$\frac{\text{Volume of biodiesel}}{\text{Volume of oil}} \times 100 \quad (3)$$

To investigate the effect of the oil-to-methanol ratio and the use of CuO-NPs on biodiesel yield, different experimental runs were conducted using 1:1, 1:2, 1:4, 1:6, 1:8, 1:10 and 1:12 oil-to-methanol ratios. The experiments were performed with a constant catalyst loading of 1 % oil weight and at 60 °C.

3.7. Characterization of biodiesel

Biodiesel properties including density, viscosity, saponification value, and iodine value were determined using standard methods. However, the cetane number was estimated according to an alternative method developed by Mekonnen *et al.* [24].

3.7.1. Determination of saponification value

Biodiesel (1 g) was weighed and dissolved in 10ml of ethanol followed by the addition of 25ml of 0.5N ethanolic KOH to the sample-solvent mixture and refluxed for 30mins. Afterward, the sample is allowed to cool until it reaches room temperature. Finally, 2-3 drops of phenolphthalein indicator were added to the cooled solution, and the excess KOH was titrated with 0.5N HCl solution until the endpoint disappeared of pink color. The procedure for the blank titration (without sample) is similar to the sample test titration. This same process was repeated for biodiesel from the various oil-to-methanol ratios. The saponification value (S.V) was calculated using Equation 4 below.

$$S.V (mgKOH/g oil) = \frac{[56N (V_b - V_t)]}{W_s} \quad (4)$$

Where: N = Normality of KOH, V_b = Volume of HCl for the blank, V_t = Volume of HCl for the test sample, ml, W_s = Weight of biodiesel sample.

3.7.2. Determination of iodine value

In one flask, 1 g of biodiesel sample is added to be dissolved as a test, and the second flask containing only solvent is used as a blank. In both flasks, 20 mL of Wij's solution was added, mixed thoroughly and incubated in the dark for about 30 min. Subsequently, 10 mL of Wij's solution was added to each test sample, rinsing the beaker sides with 50 mL of distilled water. The test and blank samples were titrated with 0.1 N sodium thiosulfate ($Na_2S_2O_3$) aqueous solution until the color changed to pale straw. Next, 1 mL of starch indicator was added into both flasks, and al-

teration of the color to purple was observed. The solution was again back-titrated until the purple color changed to colorless. This same process was repeated for biodiesel from all oil-to-methanol ratios. Finally, the iodine value was determined by equation 5.

Iodine Value (g iodine/100g oil)

$$= \frac{[12.69N (V_b - V_t)]}{W_s} \quad (5)$$

Where: N = Normality of $Na_2S_2O_3$, V_b = Volume of $Na_2S_2O_3$ for the blank sample, ml, V_t = Volume of $Na_2S_2O_3$ for the test sample, ml, W_s = Weight of sample.

3.7.3. Determination of Cetane Number

The cetane number was estimated using an alternative method developed by Mekonnen *et al.* [24], which relies on the biodiesel saponification and iodine values according to equation 6.

$$CN = 46.3 + \frac{5458}{SV} - 0.225IV \quad (6)$$

Where CN is the Cetane number, SV the saponification value and IV the iodine value.

4.0 RESULTS AND DISCUSSION

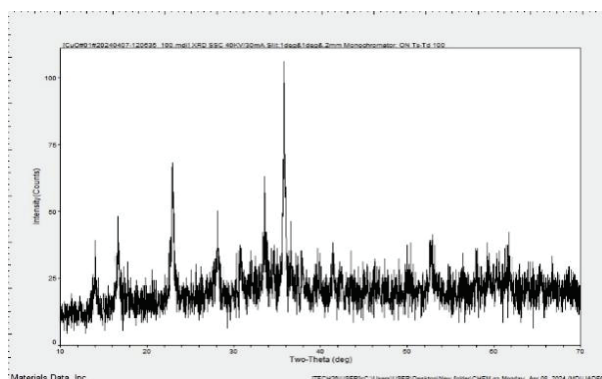
The characteristics of as received waste frying oil are shown in Table 1. The free fatty acid is more than two times higher than the 2.5% required for transesterification reaction. High FFA lead to soap formation with KOH and esterification reaction will be significant, reducing biodiesel yield. This indicates that waste frying oil in this study need to be pretreated to reduce the FFA content to less than 2.5%.

Table 1. Characteristics of WFO

S/N	WFO characteristic (Unit)	Value
1	Density at 20°C (g/cm^3)	0.9089
2	Acid value (mg KOH/g oil)	11.92
3	Kinematic Viscosity at 40 °C (mm^2/s)	45.96
4	Free fatty Acid (%)	5.96
5	Saponification Value(mg KOH/g oil)	218.67
6	Molecular weight (g/mol)	814.03

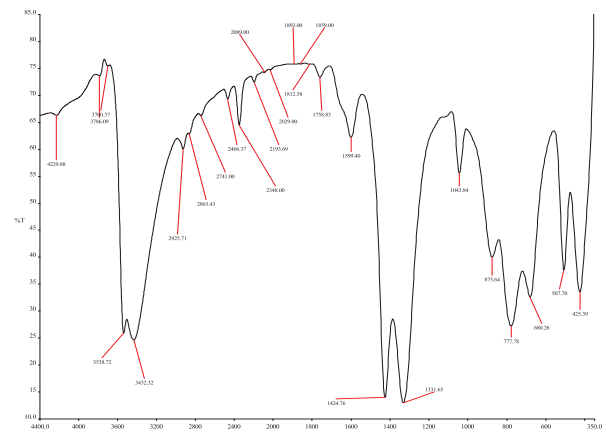
4.1 Characterization of CuO Nanoparticle

4.1.1. XRD analysis: As shown in Fig. 5, the XRD diffraction pattern exhibits sharp peaks at 2-theta (2θ) values at 15°, 17°, 23°, 28°, 34° and 36° indicating that the sample is crystalline CuO and matches the monoclinic phase [20]. The calculated average crystallite size of 16.34 nm was obtained from XRD peak width analysis using the Debye Scherrer equation. The XRD results are in good agreement with a similar previous report on CuO-NPS prepared from the precursors in this study [20].

**Fig. 6.** XRD graph of CuO-NPs.

4.1.2 FT-IR analysis:

The of FT-IR spectra of the synthesized CuO nanoparticles is shown in Fig. 7. The spectrum shows prominent peaks in three regions namely; 700- 1000 cm^{-1} , 1300- 1500 cm^{-1} , and 3200- 3600 cm^{-1} . The absorption peak at around 3538.72 cm^{-1} and 3432.32 cm^{-1} in the FT-IR spectra of CuO-NPs respectively, was caused by O-H stretching of the adsorbed water molecules. The non-existence of absorption peaks at 3300-3400 cm^{-1} indicates the absence of hydration moisture on the CuO-NPs. The absorption peaks within 700 to 1000 cm^{-1} of the spectra vibrational band at 680.26 cm^{-1} and 777.78 cm^{-1} suggest the presence of a Cu-O bond which agrees with the literature [20].

**Fig. 7.** FT-IR spectra of CuO-NPs

4.2. Effect of oil-to-methanol ratio on biodiesel yield.

The batch transesterification experiments were conducted at eight different oil-to-methanol molar ratios including 1:1, 1:2, 1:4, 1:5, 1:6, 1:8, 1:10, and 1:12 at 1% wt of oil and 60°C. Biodiesel yield increases with an increase in methanol ratio from 1:2 to 1:8, as shown in Fig. 7.

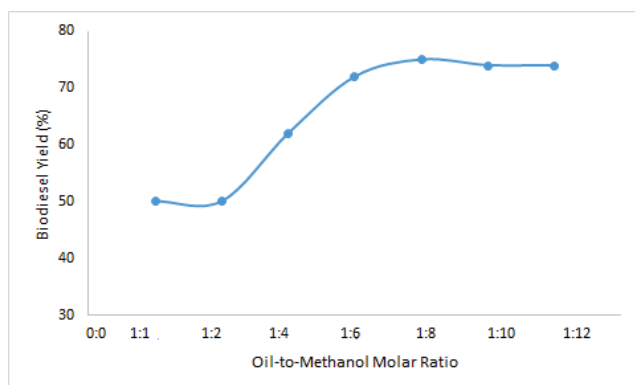


Fig. 8. Effect of oil-to-methanol ratio at 1 % catalyst loading, temperature of 60°C and reaction time of 120 minutes.

The maximum conversion was observed at a 1:8 oil-to-methanol ratio, with a 74% biodiesel yield after a 120-minute reaction time (Figure 8). This is in line with findings in the literature which indicate that an oil-to-methanol ratio below or above a critical value could result in lower biodiesel yields at a given temperature, reaction time, and catalyst loading [23, 25].

As in Fig. 8, the oil-to-methanol ratio beyond 1:8 (1:10 and 1:12) do not appear to increase biodiesel yield at 1% catalyst loading at 60 °C. Some studies have reported a lower biodiesel yield when the oil-to-methanol ratio exceeds the optimum value [25]. This is because, at a high molar ratio of methanol-to-oil, the methanol there is increased solubility of glycerol in excess methanol which interferes with the separation of glycerin. As glycerin remains in solution, it drives the equilibrium back to the left, favoring the formation of glycerides and decreasing biodiesel production [26].

4.3. Physiochemical properties of synthesized biodiesel

To evaluate the quality of the synthesized biodiesel, some physiochemical properties such as Iodine value, saponification value, density and cetane number were measured (Table 2).

Table 2: Physicochemical properties of biodiesel

Parameter	Value	ASTM (D6751)
Optimum Oil /methanol ratio	1.8	-
Optimum Catalyst loading (%)	2	-
Temperature (°C)	60	-
Reaction time (minutes)	120	-
Biodiesel Yield (%)	85	-
Density at 20 °C g/cm ³	0.82	0.8-0.90
Kinematic Viscosity at 40 °C (mm ² /s)	4.2	1.9-6.0
Iodine value (g iodine/100g Fat)	50.2	80-106
Saponification value(mg KOH/g oil)	114.8	150.1
Cetane number	82.5	> 50

Table 2 shows the properties of the biodiesel produced at 1:8 oil-to-methanol ratio and 1 % wt. catalyst loading at a reaction temperature of 60 °C and 2 hours reaction time. The density, viscosity, and iodine values are within the ASTM standards. However, the saponification value of 114.8 was higher than the 150.1 and is not in the range of ASTM for biodiesel fuel standards. This may be related to the source of the waste frying oil. The low saponification value result from longer fatty acids chain as the number of free carboxylic acid group decrease per unit fat or oil mass. The lower the saponification value, the larger the molecular weight of fatty acids in the glycerides [27].

5. CONCLUSIONS

This work has applied CuO-NPs as a catalyst to convert waste frying oil to biodiesel and has demonstrated the potential of using CuO-NPs as an alternative catalyst to basic hydroxides such as NaOH and KOH for the transesterification of WFO for sustainable biodiesel production in Nigeria. Biodiesel yield from WFO catalyzed by CuO-NPs

increases with an oil-to-methanol ratio as well as catalytic loading, both of which have optimum values. The oil-to-methanol ratio of 1:8 and catalyst loading of 2.5% wt oil produces the highest biodiesel yield at 60 °C and 2 hours reaction time.

Utilizing CuO-NPs for biodiesel presents a promising avenue for enhancing the efficiency and sustainability of biodiesel synthesis processes. Further studies that integrate more parameters such as WFO fatty acid profiles, reaction time, reaction temperature, catalyst particulate size, and cost in the optimization process are required to enable the development of a protocol for low-cost biodiesel that is cheap and affordable in Nigeria.

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ASSESSMENT OF WATER QUALITY FOR SMALL HYDROPOWER DEVELOPMENT ALONG RIMA RIVER AT GIDAN ALKALI, WAMAKO, SOKOTO STATE, NIGERIA.

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Abstract: This study examines the physical, chemical and biological attributes along Rima River for small hydropower development (SHD) at Gidan Alkali, Wamako, Sokoto State, in the downstream flow of Goronyo dam. Gidan Alkali (Wamako) lies on Latitude 13°04.452'N and Longitude 005° 07.735'E with an elevation of 235m. The samples were collected from four locations (Gidan Shirgi, Dundaye, Gidan Alkali and Wamako) in both Kware and Wamako local government area. Instrumentation analysis was adopted to test the attributes of each sample via experiment in the laboratory. It was revealed that some of the parameters were within permissible limit of the WHO and NDSM standard guidelines while some were not. The samples were brownish in color with high turbidity concentration (892, 885, 850 and 15 NTU). Turbidity is among the most essential parameters to be considered when planning for SHD. Its high concentration renders the water unsafe for SHD due to sediment accumulation and scaling of turbine blades causing inefficiency during power generation. Nitrate levels was within the permissible level; therefore, the water was less prone to algae growth neither to clog the penstock of the hydropower plant nor cause inefficiency in operation. The water needs clarification and treatment before small hydropower development.

Keywords: Downstream Surface water samples, Quality, Small Hydropower, Physical, Chemical and Biological attributes

1. INTRODUCTION

Hydropower is a critical source, providing 71% of renewable energy globally, but the construction and operation of hydropower plants, including small ones, often lead to changes in river morphology, water quality, sediment transport, and biodiversity [17]. Hydropower is the most important source of renewable electricity generation – 86.3 %, and essential to operate the other sources of renewable energy that is random generation [16]. Water quality standards for hydroelectric power projects are crucial for ensuring environmental compliance and operational efficiency, focusing on parameters like dissolved oxygen, pH, turbidity, and contaminants [15]. Baseline Water Quality Assessment conducted before construction to understand natural conditions of the hydro-

power proposed site is highly essential [15]. By focusing on key parameters and adhering to regulatory guidelines, hydroelectric facilities can minimize their environmental impact while ensuring reliable energy production [15]. Hydropower developers must evaluate and manage the following water quality indicators: Dissolved Oxygen (DO), Temperature, pH Levels, Turbidity and Sediment Load, Nutrient Levels (Nitrogen and Phosphorus), Heavy Metals and Toxic Substances [15]. Maintaining high water quality standard (s) is essential for the sustainability and efficiency of hydroelectric power project(s) [15]. The water quality downstream hydropower plant depends mainly on the quality of water from the upstream reservoir [16]. Each type of water source has its own physicochemical and biological characteris-

tics, varying from region to region, depending on the mineralogical composition of the crossed areas, by the contact time, temperature, weather conditions, etc. Water accumulated in reservoirs has the physical - chemical qualities significantly different from water flowing in the river, before the dam construction and the hydropower development [16].

Small hydropower projects are hydroelectric power projects designed to serve small communities or industrial plants, mostly operating off-grid. The generation capacity for these projects typically varies from country to country, with generally accepted upper limit of up to 10MW. These projects are particularly suitable for runoff river (RoR) schemes, which utilize diverted river flow for operation. Given the reliance on water, it is crucial to assess water quality at potential sites to ensure the safe and sustainable operation of the plant. The permissible levels of contaminants in water quality, especially for hydropower, are not universally standardized and can differ depending on national regulations. However, the World Health Organization (WHO) provides guidelines for drinking water quality, which can be used as a reference for setting national standards [13]. Currently, specific water quality standards for the impact of hydropower facilities have not been established [11]. Turbidity is one of the most challenging contaminants affecting water quality in rivers, streams, and dams for hydropower projects. Excessive trace elements in water can harm aquatic life and reduce the efficiency of hydropower plants. High turbidity levels can cause sediment accumulation in reservoirs and on turbine blades, decreasing turbine efficiency and overall power generation. Water with low

pH (acidic) can lead to the corrosion of metal components in turbines and infrastructure. Conductivity, which measures water's ability to conduct electrical current, is another important factor in hydropower projects. Elevated conductivity levels can indicate the presence of dissolved salts and chemicals, potentially affecting hydropower equipment's efficiency and longevity. Additionally, water temperature plays a role, as higher temperatures can increase evaporation rates, reducing water availability for power generation. High levels of Total Dissolved Solids (TDS) can lead to corrosion and scaling in turbines and pipes. Elevated nitrate levels in water can lead to eutrophication, causing excessive growth of algae and aquatic plants, which can clog turbines and reduce hydropower generation efficiency. Water quality is assessed in terms of physical, chemical, and biological contaminants [2,7,12]. Physical contaminants, such as suspended solids, impact water's appearance, color, odor, and turbidity [10,6,8]. These solids can contain pollutants harmful to human health and are typically removed through sedimentation or filtration [7,8,9]. Chemical contaminants can be inorganic or organic, with examples including heavy metals, pesticides, and pharmaceutical products [10,8,1]. These contaminants may originate from industrial activities, agriculture, or natural processes [14]. Microbiological examination of water is essential to ensure it is free from pathogens, with several methods available for removing biological contaminants, such as oxidation, ultraviolet radiation, distillation, and biologically active carbon filtration [3,5]. This study assesses contaminants along the Rima River at four distinct sampling sites during the dry season for small hydropower development at Gidan Alkali. It adopts the World Health Or-

ganization (WHO) water quality standard guidelines and compares the concentration of contaminants with the standards set by the Department of Standards and Meteorology in the Ministry of Industry, Nepal. Most water quality standards in developing countries align with WHO recommendations [4].

2.0 MATERIALS AND METHODS

Different materials were used; among which sampling bottles, multimeter, test tubes, reagents etc. Instrumentation methods such as sensory evaluation and visual methods were adopted in the study. Analysis of the water samples and highlighting the implications of some contaminants to hydropower plant was carried out. The results were compared with the WHO standard for water quality in Table 2.1. The results were also compared with the tolerance limits for discharge of industrial effluents to surface waters which was issued by the department of standards and meteorology under the Nepal ministry of industry. Nepal department of standards and meteorology (NDSM) guidelines on tolerance limits for industrial effluents discharged into inland surface waters is as show in Table 2.2.

2.1 WHO and NDSM Tables.

Table 2.1 and 2.2 below shows the WHO and NDSM standard guidelines for water quality which was related to the permissible limit that can be consider for hydropower water quality

Table 2.1 World Health Organization (WHO) Standard guidelines on permissible limit for drinking water quality.

Tests Performed/Unit	Limit
General Appearance	Clear
Odour	Unobjectionable
Ph	6.5-8.5
Conductivity	1,000 max
Turbidity NTU	5max
Total Hardness EDTA mg/L	150max
Taste	Unobjectionable
Temperature °C	34.4
Total Alkalinity (as HCO ₃) mg/L	200max
Total Dissolved solids mg/L	500max
Total Solids mg/L	Not stated
Free Residual Chlorine mg/L	0.2-0.25
Free Carbondioxide mg/L	50 max
Ammonia mg/L	0.05max
Chlorine mg/L	250max
Nitrite mg/L	0.2 max
Nitrate mg/L	50max
Silica (Reactive) mg/L	40max
Arsenie mg/L	0.01max
Calcium mg/L	75max
Total Iron mg/L	0.3max
Lead mg/L	0.01max
Sulphate mg/L	100max
Cadmium mg/L	0.003max
Magnesium mg/L	20max
Salinity mg/L	480max
Sodium mg/L	200max

Hydrogen Sulphide mg/L	0.05max
BOD	3.5max
COD	120max
Mineral Oil mg/L	0.003max
Total Suspended Solids	100max
Detergents mg/L	0.01max
Phosphate mg/L	Not stated

E. coli	0
Total coliforms	0
Faecal streptococci	0

Table 2.2: Nepal department of standards and meteorology (NDSM) guidelines on tolerance limits for industrial effluents discharged into inland surface waters

No.	Parameter	Tolerance Limit
1	Total suspended solids mg/L	30 - 200
2	Particle sizes of total suspended particles	Shall pass 850 of micro sieve
3	pH	5.5 – 9.0
4	Temperature	Shall not exceed 40°C in any section of the stream within 15m downstream from the effluent outlets
5	Biochemical oxygen demand for 5 days at 20°C, mg/L	30 - 100
6	Oils and grease, mg/L, Maximum	10
7	Phenolic compounds, mg/L, Maximum	1.0
8	Cyanides (as CN), mg/L, Maximum	0.2
9	Sulfides (as S), mg/L, Maximum	2.0
10	Radioactive materials: Alpha emitters, c/ml, Maximum Beta emitters, c/ml, Maximum	10-8 10 ⁻⁸
11	Insecticides	Zero

12	Total residual chlorine, mg/L	1.0
13	Fluorides (as F), mg/L, Maximum	2.0
14	Arsenic (as As), mg/L, Maximum	0.2
15	Cadmium (as Cd), mg/L, Maximum	2.0
16	Hexavalent chromium (as Cr), mg/L, Maximum	0.1
17	Copper (as Cu), mg/L, Maximum	3.0
18	Lead (as Pb), mg/L, Maximum	0.1
19	Mercury (as Hg), mg/L, Maximum	0.01
20	Nickel (as Ni), mg/L, Maximum	3.0
21	Selenium (as Se), mg/L, Maximum	0.05
22	Zinc (as Zn), mg/L, Maximum	5.0
23	Ammoniacal Nitrogen, mg/L, Maximum	50
24	Chemical oxygen demand, mg/L, Maximum	250
25	Silver, mg/L, Maximum	0.1

2.2 Description of the Study Area.

Gidan Alkali is a village in Wamako local government area of Sokoto State, Nigeria. The village area lies on Latitude 13°04.452'N and Longitude 005° 07.735'E with an elevation of 235m. It is among the downstream flow areas of Goronyo dam in Sokoto Rima River Basin which comprises Katsina, Kebbi, Sokoto and Zamfara State in the north-western Nigeria. It has hydropower potential due to perennial river flow that passes to the area. Gidan Alkali area is a best site for Runoff River (RoR) hydropower scheme.

3.0 RESULTS AND DISCUSSIONS

Fig. 1 to 9 are the results of the water quality analysis conducted in the laboratory in order to assess the level of contaminants present in the river along the four sample sites in Kware and Wamako local government. Fig. 1 to 8 were plotted Location against contaminant concentration (mg/L), while Figure 9 was plotted location against degree Celsius ($^{\circ}\text{C}$). The results have shown that not all contaminants satisfy the WHO and NDSM standard guidelines for water quality. Turbidity is among the most essential parameters to be considered when planning for SHD. The concentration of turbidity in all samples was above the permissible limit (5mg/L). Gidan Shirgi had the highest turbidity (892NTU) while Wamako had the lowest. The presence of high turbidity concentration (892, 885, 850 and 15 NTU) in GidanShirgi, Dundaye, Gidan Alkali and Wamakohas made the water not to be safe for small hydropower development. High turbidity levels can cause sediment accumulation in the water bodies such as rivers, streams, dams etc and on turbine blades, decreasing turbine efficiency and overall power generation. With respect to nitrate, high nitrate levels can lead to eutrophication, which is the excessive growth of algae and aquatic plants. Nitrate level in all samples were within the permissible level of the WHO and NDSM standards, therefore the water is less prone to algae growth which could have clog the penstock of the hydropower plant and cause inefficiency in operation. Dundaye had the highest concentration of Arsenic (0.002mg/L) while Wamako had the lowest with 0.00mg/L. High levels of arsenic contaminants can lead to cancer (carcinogenic) to humans while for the hydro, it can cause corrosion and scaling in hydro-power infrastructure, such as turbines and pipes. Additionally, water temperature plays

a role, as higher temperatures can increase evaporation rates, reducing water availability for power generation. All the temperatures in the samples were within the permissible limit. Gidan Shirgi had the highest with 31°C while Wamako had the lowest with 28°C . Gidan Alkali had the highest total dissolved solids (TDS) with 3.4mg/L while Wamako had the lowest with 0.2mg/L. The TDS concentrations in the samples were within permissible limit. High levels of Total Dissolved Solids (TDS) can lead to corrosion and scaling in turbines and pipes. The water needs clarification and treatment before carrying out small hydropower development project. The results of the parameters test of each sample site are represented in Figs. 1 to 9.

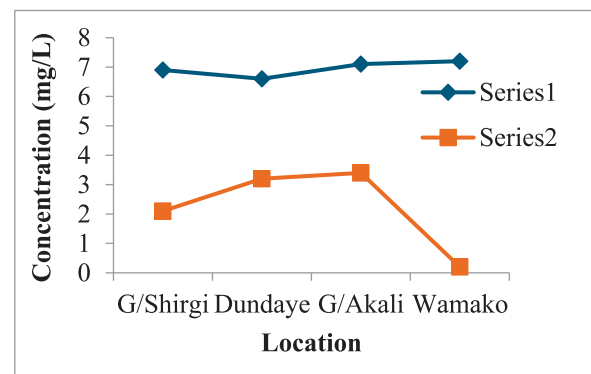


Fig. 1: pH (1) and Total dissolved solids (2)

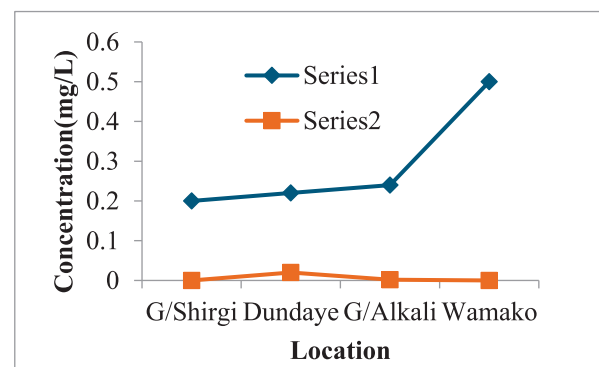


Fig. 2: Total Solids (1) and Total Suspended Solids (2)

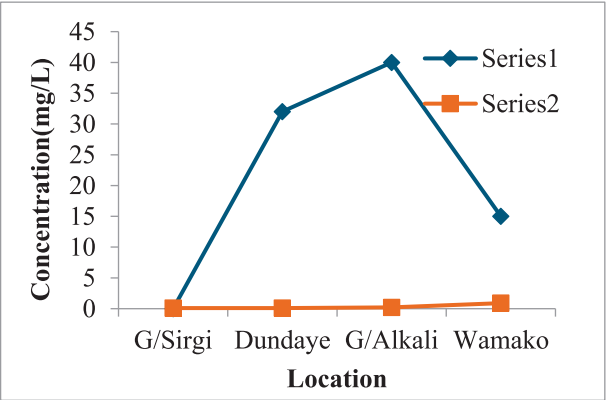


Fig. 3: Sodium (1) and Total Iron (2)

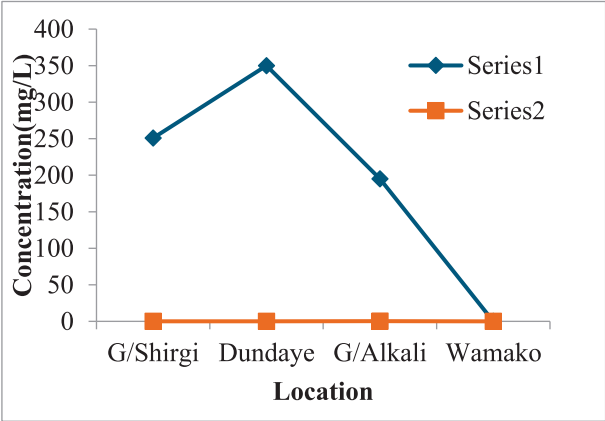


Fig. 6: Salinity (1) and Detergent (2)

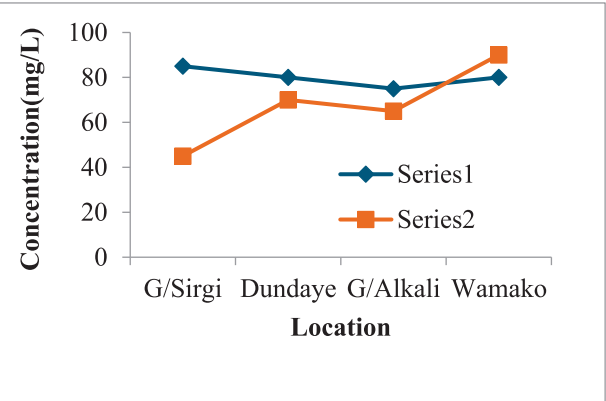


Fig. 4: Total Hardness (1) and Total Alkalinity (2)

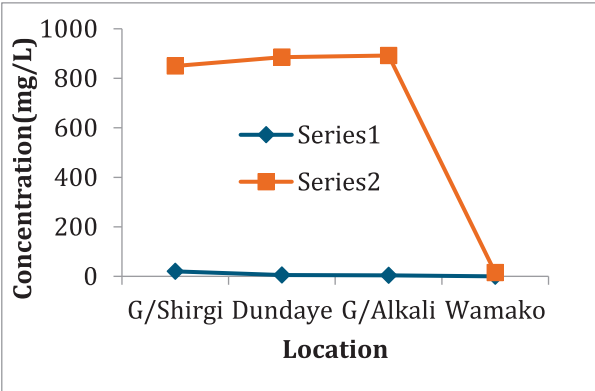


Fig. 7: E.coli (1) and Total Coliform (2)

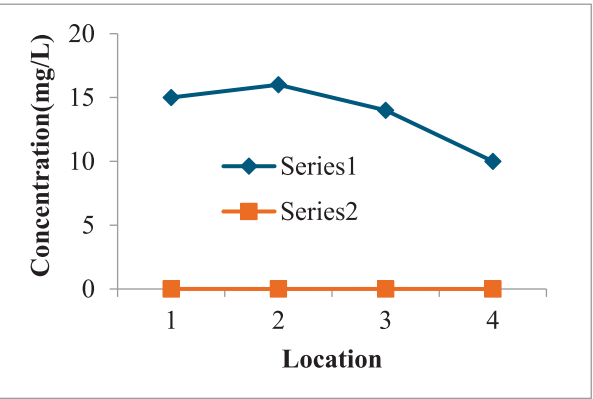


Fig. 5: Nitrate (1) and Arsenic (2)

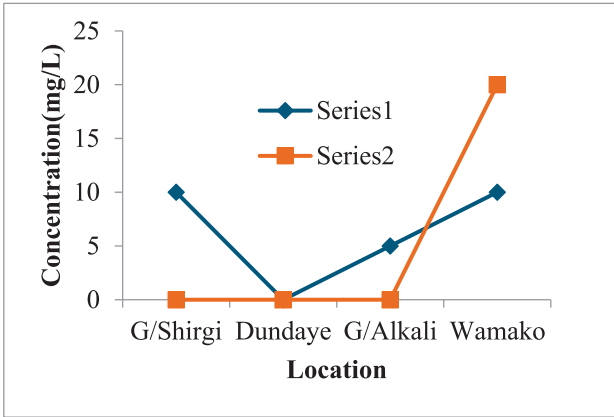


Fig. 8: Turbidity (2) and Faecal streptococci (1)

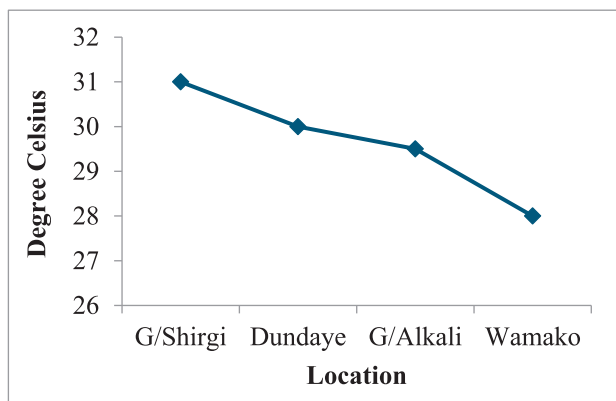


Fig. 9: Temperature

4.0 CONCLUSION

Based on the outcome of the study, it shows that all the samples in Gidan Shirgi, Dundaye, Gidan Alkali and Wamako contain turbidity (892, 885, 850 and 15 NTU) above the standards, which means the water needs clarification. Turbidity is one of the most threatening contaminants that affect the water quality of water bodies such as rivers, streams, dams, etc for hydropower project and other purposes. However, the presence of certain trace elements in excess can have detrimental effects on aquatic life and, by extension, on the efficiency and operation of hydropower plants. High turbidity levels can lead to the accumulation of sediments in water bodies and on turbine blades, reducing the efficiency of the turbine and overall power generation. With respect to nitrate, high nitrate levels can lead to eutrophication, which is the excessive growth of algae and aquatic plants. Nitrate level in all samples were within the permissible level of the WHO and NDSM standards, therefore the water is less prone to algae growth which could have clog the penstock of the hydropower plant and caused inefficiency in operation. Since not all the parametric test values of the water samples collected along Rima River satisfied the WHO and NDSM standards, the water should not be seen as safe water for small hydro-

power development (SHD). The water needs treatment before any small hydropower development project. The results of the study will serve as a database for small hydropower developers, Sokoto State Water Board (SSWB), Nigeria Standard of Drinking Water Quality (NSDWQ) and World Health Organization (WHO) in updating their water resources planning and management along the Rima River within the study area. Run-of-the-river (RoR) is the most suitable and sustainable small hydropower scheme for Gidan Alkali village

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Alphabetical List of Abbreviations and Meanings

Abbreviation	Meaning
CAGR	Compound Annual Growth Rate
CBG	Compressed Biogas
CH ₄	Methane
CNG	Compressed Natural Gas
CO	Carbon Monoxide
COP26	26th Conference of the Parties (United Nations Climate Change Conference)
CO ₂	Carbon Dioxide
C ₂ H ₆	Ethane
C ₂ H ₆ , C ₃ H ₆ , C ₄ H ₈	Ethane, Propylene, Butylene
C ₃ H ₈	Propane
C ₄ H ₁₀	Butane
ECN	Energy Commission of Nigeria
EV	Electric Vehicle
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HC	Hydrocarbons
H ₂	Hydrogen
ICE	Internal Combustion Engine
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
JENRR	Journal of Energy Research and Reviews
LPG	Liquefied Petroleum Gas
MJ/kg	Megajoules per kilogram

MSME	Micro, Small, and Medium Enterprises
Mt	Metric Tonne
NCEE	National Centre for Energy and Environment
NCEEC	National Centre for Energy Efficiency and Conservation
NCPRD	National Centre for Petroleum Research and Development
NGV	Natural Gas Vehicle
NIPCO	Nipco Gas Nigeria Limited
NNPC	Nigerian National Petroleum Company
NO _x	Nitrogen Oxides
N ₂	Nitrogen
O ₂	Oxygen
PM	Particulate Matter
PSI	Pounds per Square Inch
PSV	Public Service Vehicle
Pi-CNG	Presidential Initiative on Compressed Natural Gas
SO _x	Sulfur Oxides
TES	Total Energy Supply
UN	United Nations

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