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EXTRACTION OF GLUCOSE SYRUP FROM CASSAVA PEELS THROUGH HYDROLYSIS FOR THE PRODUCTION AND PHYSICOCHEMICAL PROPERTIES OF BIOETHANOL

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ABSTRACT

Cassava peels was converted to ethanol through acid hydrolysis (H_2SO_4), and yeast fermentation. The hydrolysis was optimized by using a factorial design achieved by varying an array of factors; acid concentration, duration of hydrolysis and temperature of hydrolysis. The temperature of acid used ranged from 40°C to 100°C while the duration of hydrolysis ranged from 1-5 hours. Fermentation of 50g of Cassava Peels was carried out using Saccharomyces cerevisiae at 35°C for 3 days. The highest yield of glucose (940mg/g) was observed in CPP in cassava peels hydrolysis at 100°C with 1M H_2SO_4 for 5 hours. Highest percentage yield of ethanol (15%) was observed three days of fermentation. The study demonstrate that cassava peel is a potential substrate for ethanol production with best yield of glucose achieved with 1M H_2SO_4, hydrolyzed at 100°C for 5 hours. High percentage ethanol yield was achieved with three days of fermentation using Saccharomyces cerevisiae.

KEYWORDS: Glucose syrup, Saccharomyces cerevisiae, Bioethanol, Carbohydrate

INTRODUCTION

Ethanol, a renewable and environmentally friendly alternative to fossil fuels, plays a crucial role in the global transition towards sustainable energy sources. Its production through fermentation processes offers a promising avenue for reducing greenhouse gas emissions and addressing energy security concerns. Ethanol production is a vital component of the biofuel industry, serving as a renewable alternative to fossil fuels. Ethanol, a type of alcohol, is primarily produced through fermentation, where microorganisms such as yeast metabolize sugars into ethanol and carbon dioxide. This process is widely employed due to its sustainability and potential to mitigate environmental issues associated with conventional fuel sources (Liu, 2019). Ethanol can be derived from various biomass sources, including grains, sugarcane, and lignocellulosic materials. The utilization of renewable feed stocks for ethanol production aligns with the global efforts to reduce greenhouse gas emissions and promote energy security (Balagopalan, 2011). Cassava peels are promising biomass sources for ethanol production, offering several advantages in terms of availability, sustainability, and economic viability. Cassava is a widely cultivated crop in many tropical regions, and its peels, which constitute a significant portion of the plant biomass, are often underutilized and considered agricultural waste. However, cassava peels are rich in carbohydrates, primarily starch, making them suitable substrates for ethanol fermentation (Oyeleke *et al.*, 2020). By valorizing these agricultural by-products, ethanol production can contribute to waste reduction and provide additional income streams for farmers.Yeast plays a pivotal role in ethanol fermentation by converting sugars derived from biomass into ethanol and carbon dioxide through anaerobic respiration. Saccharomyces cerevisiae, commonly known as baker's yeast, is the most widely used microorganism in ethanol production due to its high ethanol tolerance and efficiency in fermenting various sugars (Kumar et al. 2017). Yeast utilizes enzymes such as invertase and amylase to break down complex carbohydrates present in cassava peels into fermentable sugars, which are then metabolized into ethanol during fermentation (Sun and Cheng, 2016). Moreover, yeast strains can be genetically modified or engineered to enhance ethanol production efficiency and substrate utilization, thereby improving the overall economics of ethanol production from cassava peels (Zhao *et al.*, 2019).

The optimization of fermentation processes for the conversion of cassava peels to ethanol using yeast is a critical endeavor, especially in the context of pressing global challenges such as the depletion of fossil fuels, rising costs of petrol, and the need for effective waste management strategies.

With the finite nature of fossil fuel reserves becoming increasingly apparent, there is an urgent need to transition towards renewable and sustainable, energy sources. Ethanol, as a biofuel derived from renewable biomass, presents a promising alternative to fossil fuels.

However, to realize its full potential in mitigating the impacts of fossil fuel depletion, it is essential to optimize the fermentation of cassava peels to ethanol, as this unconventional feedstock's offer a sustainable source of carbon for ethanol production.

The volatility of petrol prices and the economic burden associated with fossil fuel dependency underscore the importance of developing cost-effective alternatives such as bioethanol. By optimizing the fermentation of cassava peels to ethanol, it is possible to create a viable pathway for reducing reliance on petrol and mitigating the financial risks associated with fluctuations in oil markets. However, the cost competitiveness of bioethanol hinges on the efficiency of fermentation processes and the ability to produce ethanol at scale and low cost.

Cassava peels represent significant agricultural waste streams that pose environmental challenges if not managed effectively. 'Improper disposal of these biomass residues: can lead to soil and water pollution, greenhouse gas emissions, and negative impacts on human health. By optimizing fermentation processes to convert cassava peels into ethanol, it is possible to valorize these agricultural by-products, turning waste into a valuable resource. This approach not only addresses waste management condemns but also contributes to the circular economy by closing the loop on agricultural waste utilization.

The main objective of the work is the extraction of glucose from cassava peels using acid hydrolysis for bio-ethanol production.

The specific objectives of this study are to determine the impact of temperature on the acid hydrolysis of cassava peels in order to identify the temperature that enhances effective breakdown of the biomass. The study also aims to examine the effect of hydrolysis duration on glucose yield to establish the optimal time required for maximum sugar production. In addition, it evaluates the effect of acid concentration on glucose yield to determine the concentration that promotes efficient hydrolysis. Finally, the study seeks to produce bio-ethanol from the glucose obtained using Saccharomyces cerevisiae, in order to assess the feasibility of converting cassava peels into bio-ethanol.

The optimization of fermentation processes for the conversion of cassava peels to ethanol using yeast holds significance across 4 various domains, notably in energy security, environmental sustainability, waste valorization, economic development and cost competitiveness. By providing a renewable alternative to fossil fuels, bioethanol contributes to reducing dependency on finite and geopolitically sensitive oil reserves, thereby - enhancing energy security. Additionally, ethanol production from agricultural waste streams like cassava peels helps mitigate greenhouse gas emissions, reduce environmental pollution, and promote sustainable land use practices, thus bolstering environmental sustainability.

CASSAVA

Cassava (Manihot esculenta) is a widely cultivated tropical root crop known for its resilience, adaptability, and versatility, making it a staple food for millions of people. in tropical and subtropical regions worldwide. Renowned for its ability to thrive in poor soil conditions and withstand drought, cassava plays a crucial role in food security and livelihoods, particularly in sub-Saharan Africa, Asia, and Latin America. (Chandel *et al.,* 2018) The plant's tuberous roots are rich in carbohydrates, primarily starch, making cassava an important source of energy in many diets.

Additionally, cassava offers a range of secondary nutritional benefits, providing essential vitamins and minerals such as vitamin C, calcium, and iron (Falconer. 1990). Beyond its dictary significance, cassava serves various industrial purposes, including the production of biofuels, starch, and animal feed. Furthermore, cassava foliage and peels can be utilized as animal feed, further enhancing its value as a multipurpose crop (Okoli *et al.,* 2014). Despite its numerous advantages, cassava cultivation and processing face challenges such as pests, diseases, and post-harvest losses, highlighting the need for sustainable agricultural practices and technological innovations to maximize cassava's potential in addressing food security and rural development challenges.

Cassava (Manihot esculenta) is a perennial shrub characterized by its robust nature, with woody stems and a prominent tuberous root system. The size of cassava plants varies depending on factors such as variety and growing conditions, but they typically range from 1 to 3 meters in height, with some varieties reaching up to 5 meters (Balagopalan, 20l1). Cassava belongs to the. family Euphorbiaceae and is classified as a dicotyledonous plant. The leaves of. cassava are palmately lobed, arranged spirally along the stem, and can vary in shape from ovate to lanceolate, with prominent veins. The color of cassava leaves ranges from light to dark green, depending on factors such as age and nutrient status. The tuberous roots, which serve as the main storage organ of the plant, vary in size and shape but are typically elongated and cylindrical, with a rough, brownish outer skin (Okogbenin, 2012). Cassava roots come in different colors, including white, yellow, and pink, depending on the variety. Overall, cassava's nature, size, height, class, and color make it a versatile and adaptable crop with diverse uses in agriculture, food, and industry.

Cassava (Manihot esculenta) belongs to the following taxonomic classification:

Kingdom: Plantae
Phylum: Angiosperms (Magnoliophyta).
Class: Eudicots (Magnoliopsida)
Order: Malpighiales
Family: Euphorbiaceae
Genus: Manihot
Specie: Manihot esculenta

Harvesting of cassava involves several stages to ensure optimal yield and quality of the tuberous roots. Typically, cassava is harvested between 8 to 24 months after planting, depending on the variety and intended use (Chandel *et al.*, 2018). The first step in harvesting involves uprooting the cassava plants using hand tools or machinery, being careful not to damage the roots. Once uprooted, the tuberous roots are carefully removed from the soil and separated from the stems. After harvesting, the cassava roots are subjected to post-harvest processing, which may include washing, peeling, and trimming to remove any 'soil, debris, or damaged portions.

Proper handling and storage are crucial to prevent post-harvest losses and maintain the quality of the roots. Cassava roots are highly perishable and should be processed or consumed soon after harvesting to preserve their nutritional value and minimize spoilage (Okoli *et al.*, 2014).

METHODOLOGY

Processing of Cassava Peel Powder: The cassava root tubers were washed with tap water to remove adhering dirt, peeled. The peels were sun-dried, and blended to form cassava peel powder (CPP). This was stored in a plastic container with lid and labeled CPP.

Extraction of Glucose from CP: This was achieved by acid hydrolysis. The process was optimized by evaluating the impact of acid (Sulphuric acid) concentration, temperature of hydrolysis and duration of hydrolysis on glucose yield.

Optimization of Hydrolysis

The Hydrolysis of the substrate Cassava Peel was optimized using an Orthogonal array of factors; temperature, acid concentration and duration of hydrolysis. The method involved varying the factors in an array of low, medium and high. For temperature, the low was 40°C, medium 70°C and high 100°C. For acid concentration, the low was 1M, medium 3M and the high 5M, while for duration of hydrolysis, the low was 1 h, medium 3h, and the high 5h.

Examination of Hydrolysate for Glucose Content

This was analyzed using a Refractometer. The brix reading (amount of glucose in 100 g of sample) was taking before and after hydrolysis.

Fermentation of Hydrolysate

This was carried out using yeast (Saccharomyces cerevisiae). Fifty gram (50 g) of CPP was hydrolyzed using the optimized conditions. The hydrolysate was sterilized at 121°C for 15 minutes in an autoclave, and transferred into a 1 L plastic container (previously sterilized using 95% ethyl alcohol). A 5 g portion of standard grade Saccharomyces cerevisia was then added and the container locked to create an anaerobic environment for fermentation. The set-up was place in an incubator at 35°C for 3 days.

Distillation of Fermented Broth: After fermentation the fermented broth was poured into a distillation flask of a distillation apparatus fitted with a condenser. The flask was then mounted in a heating mantle and the temperature set at 80°C. Upon collection of the distillate, the percentage ethanol content was determined using an alcohol meter.

Evaluation of Percentage Ethanol in Distillate

The percentage ethanol content of the distillate was determined using an alcohol meter. The alcohol meter was inserted into the distillate in a 100 ml measuring cylinder, and the percentage ethanol recorded.

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RESULT AND DISCUSSION

RESULT

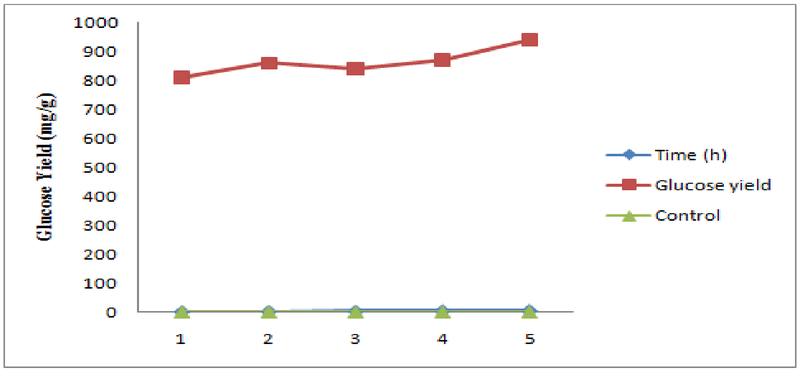
The glucose yield from the hydrolysis of cassava peel powder (CPP) varying the acid concentration (1M to SM) and temperature of hydrolysis (40°C to 100°C) is shown in Table 1. Glucose yield in Cassava Peel hydrolyzed with 1M H2S04 ranged from 241 mg to 820 mg, with highest yield recorded at 100°C. Glucose yield in Cassava Peel hydrolyzed with 3M H2SO4 ranged from 160 mg to 375 mg, with highest yield also recorded at 100°C. Hydrolysis with 5M H2SO4 had glucose yield ranging from 233 mg to 350 mg, with highest yield observed at 70°C.

Table 1: Glucose Content (mg/g) of Cassava Peel Powder after 1 H of Hydrolysis with Sulphuric Acid

Concentration	Temperature °C	CPP	Control
IM	40	241+0.01	0.00
1M	70	342+0.05	0.00
1M	100	820+0.02	0.20
3M	40	160+0.02	0.20
3M	70	218+0.03	0.20
3M	100	375+0.07	0.20
5M	40	265÷0.03	0.20
5M	70	350+0.07	0.20
5M	100	233+0.08	0.20

Results are means of duplicate treatments + standard deviation
Key: CCP: Cassava peel powder.

Figure 1 shows the result of the effect of duration (Time) on the hydrolytic process using the best outcome of temperature and acid concentration (100°C and 1M respectively).Duration of hydrolysis used ranged from 1 hour to 5 hours. Generally, there was an increase in glucose content as the duration of hydrolysis increases from 1 hour to 5 hours. Highest yield was observed at 5 hour duration of hydrolysis with cassava peels having the highest yield of 940 mg/g.



Glucose Content (mg/g) of Cassava Peel Powder Hydrolysis with

1M sulfuric acid at 100°C for 5 hours

The result of the percentage ethanol content of the distillate of the fermented broth is shown in table 2. The result showed that Cassava Peel fermented for 120 hours (5 days) had the highest ethanol content of 15% followed by 96 h and 72 h; 9% and 5% respectively.

Table2: Percentage Ethanol content of Distillate of Fermented CPP broth

Time (h)	% Ethanol
72	5
96	9
120	15

Table 3 Physicochemical Properties

Property	Typical value
Appearance	Clear, colourless liquid
Odor	Characteristic alcohol smell
Boiling point	78.3^{0}C
Melting point	-114.1^{0}C
Density (at 20^{0}C)	0.789 g/cm^2
Specific gravity (20^{0}C)	0.789
Refractive index (20^{0}C)	1.361
Flash point	13^{0}C
Viscosity (20^{0}C)	1.2 mPa-s
Solubility in water	Completely miscible
Chemical formula	C_2H_50H
Molar mass	46.07 g/mol
pH (in aqueous solution)	6.5-7.5
Acidity (as acetic	0.01 -0.05% (depend purification)

solution)	
Ethanol purity	90 - 99.9% (depend on distillation
Ash content	Very low (<0.01%)
Water content	0.1 - 10%(varies grade)

DISCUSSION

The results from Table 1 clearly show that both acid concentration and temperature significantly influenced glucose yield. Among the combinations tested, hydrolysis at 1M HSO and 100°C produced the highest glucose yield (820 mg/g) for 1 hour, whereas higher acid concentrations (3M and 5M) did not show better performance; in fact, they produced lower yields overall. This suggests that excessively high acid concentrations may lead to degradation of released sugars (e.g., formation of inhibitory compounds like furfural), reducing the measurable glucose content. The highest yield for 1M and 3M was at 100°C, while for 5M, the highest yield was at 70°C, likely because further temperature increases with high acid concentrations could accelerate sugar degradation or caramelization. These trends are consistent with previous studies on acid hydrolysis of lignocellulosic biomass, which have found that moderate acid levels balance effective hydrolysis with minimal sugar degradation (Sun and Cheng, 2002).

Figure1 illustrates the effect of varying hydrolysis duration (at IM $HaSO_4$ and 100°C). There was a steady increase in glucose concentration from 1 hour (820 mg/g) up to 5 hours, where the maximum yield reached 940 mg/g. Progressive saccharification is observed over time, as longer exposure allows more extensive breakdown of cellulose and hemicellulose fractions of Cassava Peel. The potential trade-off with prolonged hydrolysis, where very long durations might eventually lead to sugar degradation; however, within the tested 5-hour window, continued increase in yield suggests this threshold was not yet reached. Optimizing duration is therefore key to maximizing sugar release while avoiding unnecessary energy input or degradation risks.

The fermentation results (Table 2) indicate that fermentation time directly influenced ethanol production, with ethanol concentration rising from 5% at 72 hours, to 9% at 96 hours, and peaking at 15% at 120 hours (5 days). Active fermentation phase extended to at least 120 hours, with yeast maintaining fermentative activity throughout. The increasing ethanol concentration also implies that the glucose concentration obtained from hydrolysis was sufficiently high to support prolonged fermentation.

A 15% ethanol yield from cassava peel hydrolysate is quite significant and indicates high conversion efficiency, especially for a substrate often considered low-value waste. This confirms CPP's promise as a viable feedstock for bioethanol production.

Overall, the optimized process (1M H2SO4, 100°C, 5-hour hydrolysis, followed by 120-hour fermentation) proved effective, resulting in high glucose yields and ethanol production. The experimental design allowed systematic evaluation of key parameters, providing clear guidance on optimal processing conditions. These results are consistent with and add to existing literature highlighting cassava peel as an underutilized resource for sustainable bioethanol production (Oyeleke *et al.*, 2012); The process could contribute to reducing environmental burden of cassava waste while supporting renewable energy initiatives. In the physicochemical properties of the bioethnol show that the density of the bioethano is $0.789g/cm^2$. The specific gravity 0.789 the refractive index is 1.361

and the flash point is 13^0C while the viscosity is 1.2mPa.s. Also the ash content is very low and pH is aqueous solution is 6.5 - 7.5.

CONCLUSION

In conclusion, the production of bioethanol from cassava peel through acid hydrolysis and fermentation presents a viable and sustainable pathway for converting agricultural waste into a valuable biofuel. The step-by-step process, encompassing meticulous cassava peel preparation, efficient acid hydrolysis to saccharify complex carbohydrates, careful neutralization to optimize pH, robust yeast-mediated fermentation, and effective ethanol recovery through distillation, highlights a comprehensive approach. This method not only offers an environmentally friendly alternative to fossil fuels but also addresses waste management challenges associated with cassava processing. While each stage requires careful optimization of parameters such as acid concentration, temperature, time, and yeast strain, the successful implementation of this process holds significant potential for enhancing energy security and promoting a circular bioeconomy, particularly in regions with abundant cassava resources like Nigeria. Further research focusing on process intensification, cost reduction, and scale-up will undoubtedly contribute to the widespread adoption and commercial viability of cassava peel-derived bioethanol.

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INTEGRATING WASTE PICKERS INTO WASTE MANAGEMENT SYSTEM FOR SUSTAINABLE ENVIRONMENT: AN OVERVIEW

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Abstract

This paper defined waste pickers as individuals who collect, sort, and sell recyclable materials (plastics, paper, metal, glass). A waste management system was referred to as the organized process of handling waste from the moment it is created until its final disposal, in a way that protects human health and the environment. Some of the reasons why integrating waste pickers with waste management system is imperative is because waste picking reduce landfill use and greenhouse gas emissions; provide low-cost recycling services, improves livelihoods and dignity. The framework for integration was considered under the following subtopics: legal and policy recognition, organizational integration, service based integration, infrastructure and equipment support as well as social protection and welfare. The paper mentioned the need for economic inclusion of waste pickers, capacity building and gender parity. Among the challenges to integration identified was informality and mistrust while gradual formalization and dialogue was proffered as a solution. If waste pickers are properly integrated into waste management system, some of the measurable outcomes for the future include: higher recycling rates and reduced landfill burden;

Keywords: waste pickers, waste management system, frame work for integration, measurable outcomes

Introduction

Waste pickers

Waste pickers are individuals who collect, sort, and sell recyclable materials (plastics, paper, metal, glass). They work in streets, households, dumpsites, transfer stations, or landfills and are often part of the informal waste management sector (Dias, 2016). A broader term, often used interchangeably is scavengers. This synonym usually refers to people who retrieve reusable or recyclable items from dumpsites or landfills, the term can be considered stigmatizing, so “waste picker” is preferred in professional contexts (Hidalgo-Crespo et al., 2023).

Waste management system

A waste management system refers the organized process of handling waste from the moment it is created until its final disposal, in a way that protects human health and the environment. A waste management system is a method used to collect, transport, treat, recycle, and dispose of waste properly (Zungu-Tamo et al., 2025). The lack of proper coordination of the activities of waste pickers has led to under maximization of their true contribution to waste management.

Integrating waste pickers into a formal waste management system is widely recognized as a socially just, economically efficient, and environmentally sustainable approach.

Why integration is imperative

Integration of waste pickers into waste management system is important because waste pickers already (Wibin, (2025):

Recover 20–60% of recyclables in many cities;

Reduce landfill use and greenhouse gas emissions;

Provide low-cost recycling services;

Improves livelihoods and dignity (Deka, 2025);

Increases recycling rates;

Lowers municipal waste management costs.

Framework for integration

The framework for integration shall be considered under the following subtopics: legal and policy recognition, organizational integration, service based integration, infrastructure and equipment support as well as social protection and welfare.

A. Legal & Policy Recognition

There are reported cases of waste pickers being regarded and often treated as criminals. Though there are cases of miscreants camouflaging as waste pickers to carry out their nefarious activities, genuine crime free waste pickers abound (Kobiga, 2025). It is therefore of great importance to grant legal recognition to genuine waste pickers and prevent them from being mistaken to be hoodlums. Some of the policies that can help actualize this include:

Official recognition of waste pickers as environmental service providers.

They should be included in government legislation regarding solid waste management; For example: India's Solid Waste Management Rules recognize waste pickers as stakeholders (Kwarteng et al., 2020).

Issuance of identity cards, work permits, or licenses to waste pickers.

B. Organizational Integration

It is important to organize waste pickers since most of them work in isolation and their activities are mostly individualized. Those that work in collaboration usually do so with very local and inefficient networking. The organizational structure of waste pickers can be greatly enhanced through the steps below:

Formation of cooperatives, unions, or associations;

Contracting cooperatives for door-to-door collection (Nawaz et al., 2021);

Coordinated approach to sorting street waste;

Large scale systematization for waste recycling.

For example: SWaCH Cooperative for waste pickers in Pune, India has been organized to serve over 800,000 households (Abubakar, 2022).

C. Service-Based Integration

Waste pickers can be better integrated to maximize their service delivery and seamlessly tap into their potentials for better community based waste management. Some of the ways this can be achieved includes;

Waste pickers can be formally employed;

Door-to-door waste collection;

Source segregation awareness (Dada, 2023);

Sorting and processing at material recovery facilities (MRFs);

Operation of recycling centers;

Government may offer service fees, performance-based incentives (Kibonde and Mwasha, 2025).

D. Infrastructure & Equipment Support

Infrastructural support should be afforded waste pickers in the form of:

Personal protective equipment (PPE) including gloves, masks, boots and helmets. They should also be supported with transportation equipment like carts, pickup trucks, tricycles, or electric vehicles (Milić, 2025). Provision with sorting sheds and storage facilities should also be considered. Waste pickers should be provided with weighing scales to determine the weight of materials as well as balers for the compression of solid waste.

E. Social Protection & Welfare

There is the need to provide a framework for the social wellbeing of waste pickers. This will act as the backbone for their personal welfare and go a long way to enhance their self-worth (Milić, 2025). Some of the ways this can be accomplished are:

Health insurance and accident coverage;
Access to pensions and savings schemes;
Child education and childcare support;
Occupational health and safety training.

Economic Integration

Waste pickers are generally perceived by the public as belonging to the informal sector. This perception can be changed by institutionalized integration into the economy of the country. They can be repositioned to enjoy the same benefits available to other blue collar income earners, such benefits include (Amosu, 2021):

Guaranteed minimum prices for recyclables;
Access to microfinance and banking;
Inclusion in Extended Producer Responsibility (EPR) systems;
Direct payments through digital platforms;
In Colombia waste picker cooperatives are paid per ton of recyclables collected.

Capacity Building

It is common knowledge that most waste pickers are illiterates, school drop outs and lack skills that can attract sustainable income. Availing them with skills that can build their capacity and improve their efficiency as well as boast their financial capacity is crucial (He et al., 2024). This can be achieved by training by in:

Waste segregation;

Business management;
Quality control of recyclables;
Health and safety;
Leadership and cooperative governance training (Wilson et al., 2006).

Gender & Social Inclusion

Male dominance among waste pickers should be strongly discouraged, humiliation and oppression of the females should guaranteed through legislation as well as:

Special focus on women waste pickers;
Protection against harassment and discrimination (Oguntoyinbo, 2012);

Parity in financial remuneration opportunities;

Equal leadership opportunities.

Challenges & Solutions

Some of the challenges that stand against integration of waste pickers into waste management system and their solutions are briefly itemized in Table 1.

Table 1: Challenges to integration of waste pickers into waste management system and solutions.

Challenge	Solution
Resistance from private contractors	Hybrid models & inclusive tenders
Informality & mistrust	Gradual formalization & dialogue
Low income stability	Service fees
Health risks	PPE, insurance, training
Stigmatization	Issuance of uniforms and ID cards
Illiteracy	Informal education

Source: (Oguntoyinbo, 2012)

Measurable Outcomes for the future

Waste pickers form a great pool of environment friendly workers whose activities are largely communized and often stigmatized. If their activities are better organized and they are properly integrated into waste management system, some of the benefits that will accrue to society include:

Higher recycling rates;

Reduced landfill burden;

Improved incomes and working conditions;

More inclusive and resilient cities.

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CONSTRUCTION AND IMPLEMENTATION OF A GSM BASED ANTI-THEFT VEHICLE SECURITY SYSTEM

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Abstract

This is research work presents the construction and implementation of a gsm based anti-theft vehicle security system. This system is constructed to provide safety of vehicle through real time tracking and emergency alert capabilities. It integrates a microcontroller with a GSM module and GPS technology to detect distress signals and transmit location data to pre-registered emergency contact numbers. The electronic system upon activation typically via a discreet button or sensor, the device sends an SMS containing the vehicle's GPS coordinates, enabling quick response and possible prevention. This low cost, and portable system aims to combat the rising threat of vehicle theft by providing instant communication and traceability, especially in areas with limited security infrastructure. The work demonstrates the effectiveness of GSM communication in providing safety of vehicle security applications and its potential for wider societal immense impact.

KeyWords: GSM, Global Positioning System technology, Vehicle Security system.

Introduction

In recent years, the rate at which vehicle theft rises spontaneously became of serious concern for car owners, law enforcement agencies, and insurance companies. The proliferation of sophisticated theft techniques and the increasing value of vehicles have underscored the importance of implementing robust anti-theft security systems to safeguard vehicles against unauthorized access and theft (Boukhechba et al., 2020). The evolution of technology has revolutionized the design and functionality of vehicle security systems, offering a wide range of innovative solutions to enhance protection and deter potential thieves. With advancements in Global Positioning System tracking, biometric authentication, and machine learning, the effectiveness of anti-theft security systems has significantly improved, prompting researchers and engineers to explore new approaches to fortify vehicle security measures further (Sujatha and Gomathi, 2019).

The integration of Global Positioning System tracking technology has been instrumental in enabling real-time monitoring and location tracking of vehicles, allowing owners and law enforcement agencies to track and recover stolen vehicles efficiently (Kumar and Basavaraju, 2018). By leveraging satellite-based navigation systems, Global Positioning System -enabled anti-theft security systems can provide accurate location information, enabling swift responses to theft incidents and increasing the chances of recovering stolen vehicles intact. Furthermore, the integration of biometric authentication technologies such as fingerprint recognition and facial recognition has enhanced the security of vehicles by adding an additional layer of protection beyond conventional key-based or electronic lock systems (Kumaran et *al*., 2020). Biometric authentication systems ensure that only authorized individuals can access and operate the vehicle, reducing the risk of theft and unauthorized use significantly.

Moreover, the utilization of machine learning algorithms in anti-theft security systems has further augmented the defense mechanisms against theft attempts (Guo et al., 2017). By analyzing patterns of suspicious behavior and identifying anomalies in vehicle access and usage, machine learning algorithms can proactively detect potential threats and trigger immediate response actions to prevent theft incidents. The ability of machine learning algorithms to adapt and learn from past incidents enables security systems to continuously improve their detection capabilities and enhance the overall effectiveness of anti-theft measures.

As the demand for advanced anti-theft security systems continues to grow, researchers have focused on evaluating the performance of these systems to assess their efficacy in preventing theft and protecting vehicles (Ayyagari et *al*., 2019). By measuring key performance indicators such as theft rates, detection accuracy, and response time, researchers aim to identify the strengths and weaknesses of current security systems and propose enhancements to bolster vehicle protection further. Through comprehensive performance evaluations, researchers seek to enhance the reliability and efficiency of anti-theft security systems, ultimately reducing the incidence of vehicle theft and ensuring the safety and security of vehicles in an increasingly digitized and interconnected world.

Research Design and Methodology

Research Design

Circuit Design

The block diagram of this project work is shown below in figure 3.1.This give outline detail description of how this work was implemented and the various steps involved in it. The car anti-theft security system depicted in the block diagram integrates several components to provide robust protection against vehicle theft. The heart of the anti-theft Vehicle security system is the microcontroller, which acts as the brain, coordinating the operations of all connected devices: the GPS modem, keypad, LCD, and GSM modem.

When the vehicle owner wishes to secure his or her car, they use the keypad to enter a security code. This keypad serves as the primary user interface for arming and disarming the system. The microcontroller receives this input, verifies the code, and if correct, activates the security system. This status change is immediately displayed on the LCD, a visual output device, confirming to the user that the system is armed and ready.

Once armed, the microcontroller continuously receives real-time location data from the GPS modem. This data allows the system to monitor the vehicle's position constantly. If the car is moved without proper authorization, the microcontroller detects this unauthorized movement through the GPS data. In response, the system triggers an alert protocol.

The microcontroller then sends a signal to the GSM modem in the developed work to communicate with the vehicle owner. The GSM modem sends a text message or call to the owner's mobile phone, providing real-time information about the vehicle's location. This immediate notification enables the owner to take swift action, such as alerting the authorities or using recovery services to locate the vehicle. Meanwhile, the LCD continues to display pertinent

information, such as the status of the system and any alerts. This ensures that anyone interacting with the vehicle can see the current state of the security system

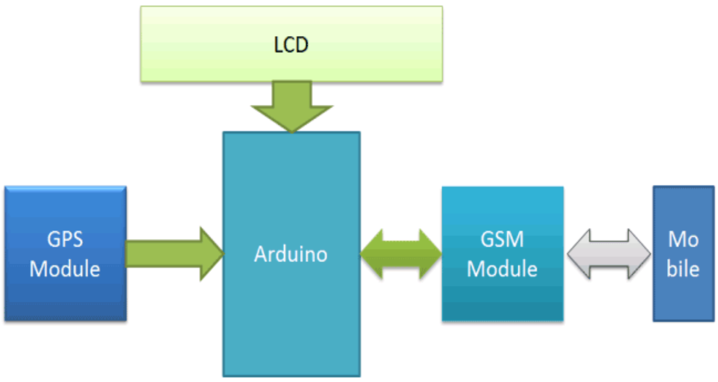

Figure 1 Block diagram of anti-theft vehicle security system

n the block diagram of the anti-theft vehicle security system, various components work together to ensure that the vehicle is protected against unauthorized access and movement. Here's a detailed explanation of the power supply, sensing unit, and control unit in this system.

Power Supply unit

The power supply is a critical component that provides the necessary electrical energy to all parts of the system. In a vehicle anti-theft system, the power supply typically draws energy from the vehicle's battery. It needs to be reliable and capable of providing stable voltage levels to ensure continuous operation of the Arduino microcontroller, GPS module, GSM module, and LCD. Power supply design might include voltage regulators to maintain consistent voltage levels and possibly backup power sources like capacitors or secondary batteries to keep the system operational in case the main vehicle battery is compromised.

Sensor Unit

The sensor unit in this system is primarily represented by the GPS module. The GPS module continuously receives signals from satellites to determine the precise location of the vehicle. This location data is sent to the Arduino microcontroller. The role of the GPS module is crucial as it allows the system to detect unauthorized movement of the vehicle. If the vehicle moves without the owner's authorization, the sensor unit detects or senses this change and triggers the control unit to initiate an alert.

Control Unit

The control unit is the heart of the system, comprising the Arduino microcontroller. The Arduino processes data from the GPS module, interprets the information, and decides on the necessary actions. It performs several critical functions:

- **Data Processing**: It receives and processes real-time location data from the GPS module.
- **Decision Making**: It determines if the vehicle is being moved without authorization by comparing current location data with predefined parameters.
- **Alert Mechanism**: Upon detecting unauthorized movement, the Arduino activates the GSM module.
- **Communication**: The GSM module, controlled by the Arduino, sends alert messages to the owner's mobile phone, providing the real-time location of the vehicle. This ensures that the owner is immediately notified of any suspicious activity or movement of the vehicle.
- **Display Information:** The Arduino also updates the LCD with relevant

- information, such as system status (armed/disarmed)
- current location data, and alert messages, providing a user-friendly interface.

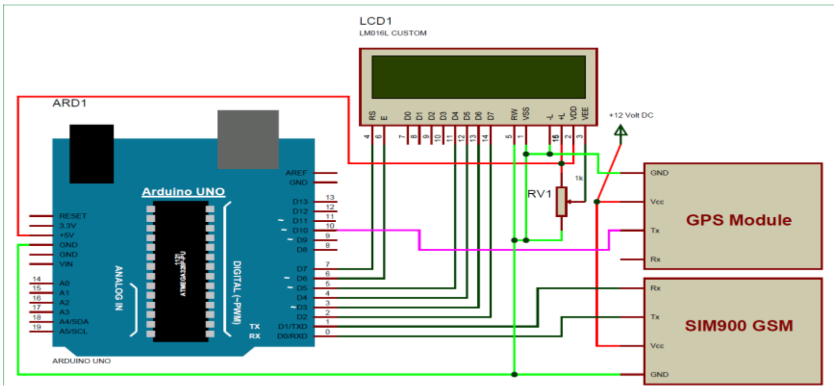

figure2.Circuit diagram of an Anti-theft vehicle security system

ircuit Connections of this Vehicle Tracking System Project is simple and is shown in the image above. Here Tx pin of GPS module is directly connected to digital pin number 10 of Arduino. By using Software Serial Library here, we have allowed serial communication on pin 10 and 11, and made them Rx and Tx respectively and left the Rx pin of GPS Module open. By default Pin 0 and 1 of Arduino are used for serial communication but by using Software Serial library, we can allow serial communication on other digital pins of the Arduino. 12 Volt supply is used to power the GPS Module.

GSM module's Tx and Rx pins of are directly connected to pin Rx and Tx of Arduino. GSM module is also powered by 12V supply. An optional LCD's data pins D4, D5, D6 and D7 are connected to pin number 5, 4, 3, and 2 of Arduino. Command pin RS and EN of LCD are connected with pin number 2 and 3 of Arduino and RW pin is directly connected with ground. A Potentiometer is also used for setting contrast or brightness of LCD.

Development and Implementation of a GSM Based Anti-Theft Vehicle Security System

The development of this project work was carried out in two phases which are: the hardware and software development. The hardware development was carried out with the prototype development which involves the arrangement of components on bread circuit board. This prototype was used in the development of the programming, to test each section and the components that make up the electronic circuit system in order to know if the circuit diagram was okay. This process was later transferred on to the permanent circuit board. In this project work, vero board was employed and the arrangements of components on it were soldered to it with the aid of solder lead and soldering iron.

Temporary Circuit Development

Temporary circuit development involved creating a prototype to test the functionality of the anti-theft vehicle security system before finalizing the development. This phase was crucial for identifying and troubleshooting issues. Here are the key steps:

The components (GPS module, GSM module, Arduino, LCD) were assembled on a breadboard, allowing for easy modifications and testing. Jumper wires were used to connect the components. All connections were secured and matched the circuit diagram. The GPS module's TX pin was connected to the Arduino's RX pin and its RX pin to the Arduino's TX pin. Similarly, the GSM module’s TX and RX pins were connected to the appropriate pins on the Arduino.TheLCD

display was connected to the Arduino using the appropriate digital pins and a potentiometer for contrast adjustment. A regulated power supply was used to power

Programming and Debugging of Programming in Arduino

- The program was uploaded to the Arduino, and the system’s functionality was tested.

Any issues were debugged by checking connections and revising the code or programming as nee

the Arduino and modules, ensuring the voltage and current ratings matched the components' requirements.

- The GPS module's location data acquisition, the GSM module's alert sending,and the LCD's information display were verified.

figure 3.3 below shows the programming of the Arduino

Figure 3.: Arduino IDE showing the HEX number and the codes.

Interfacing GPS module using computer and Ar

or interfacing GSM with computer we either need USB to Serial Converter or Arduino Board. Here we are using Arduino board to interface GPS. We only need Arduino Board, GPS module, computer and 12V/3.3V adaptor for power supply. Here we have used GPS receiver Module SKG13BL (shown in above figure).

Figure 4: Arduino Use in Interfacing a GPS

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before connecting it to the computer, we first need to remove the Arduino IC (Atmega chip) from the Arduino Board, as we only need the serial circuitry of the Arduino. This is called the Gateway mode. Removing the IC is shown in below figures:

Figure 5:An Arduino IC being removed from the Arduino board

Permanent Circuit Development

0nce the prototype was verified and all issues were resolved, the development of a permanent circuit commenced. This involved creating a more robust and reliable version of the system.PCB design software (e.g., Eagle, KiCad) was used to create a schematic of the circuit. This involved placing all components and connecting them according to the tested prototype. The PCB layout was designed, arranging components efficiently and routing the connections. Adequate space was ensured between traces to prevent short circuits.

The PCB design files were sent to a manufacturer to fabricate the PCB, producing the board with all the copper traces and component footprints. Once the PCB was fabricated, components were soldered onto the board, ensuring all components were correctly oriented and securely attached.

An appropriate enclosure was designed or selected to house the PCB and components, protecting the circuit from environmental factors and physical damage. The PCB was mounted and all connections were secured, including provisions for power supply and antennae for the GPS and GSM modules. The assembled permanent circuit was tested to ensure it functioned as expected. The system's performance was verified under various conditions, ensuring reliability over extended periods.

Testing

Testing an anti-theft vehicle security system involves several steps to ensure all components work correctly and the system effectively secures the vehicle. Here's a brief outline of the testing carried out in this project work:

In the development of this electronic circuit, GPS Module Verify the GPS module accurately to determine the vehicle's location. The Arduino was checked for Consistent data transmission. The GSM module's ability to send and receive SMS messages was tested. Ensure it can communicate

with a mobile phone. Ensure the LCD correctly displays information provided by the Arduino, such as GPS coordinates and status messages.

Confirmation was made to know if the GPS module communicates correctly with the Arduino, and the location data is processed accurately. It was checked if the Arduino can send alerts via the GSM module in different scenarios where alerts need to be sent. access to the vehicle and verify that the system sends appropriate alerts to the designated mobile device.

Principle of operation of a Vehicle Anti-theft security system

The anti-theft vehicle security system operates on the principle of continuous monitoring and real-time communication to detect and respond to unauthorized vehicle movements. At the heart of this system is a reliable power supply, typically sourced from the vehicle's battery, ensuring that all components such as the Arduino microcontroller, GPS module, GSM module, and LCD receive stable and continuous power. Upon activation, the microcontroller initializes all connected modules, ensuring they function properly.

The system begins its operation when the vehicle owner arms it using a user interface, such as a keypad or remote control. Once armed, the system enters a vigilant monitoring state. The LCD provides real-time feedback, displaying the system status and confirming that the security measures are active. The GPS module, acting as the sensing unit, continuously receives satellite signals to determine the vehicle's precise location. This real-time location data is then sent to the Arduino microcontroller, which processes the information and keeps a record of the vehicle's current position.

The microcontroller plays a crucial role by constantly comparing the current location data with the predefined stationary position of the vehicle. If the vehicle is moved without proper authorization, indicated by a

- Cutter
- Signal generator
- Oscilloscope etcetera.

Circuit Components

- GSM Module
- GPS Module
- 16x2 LCD
- Power Supply
- Connecting Wires
- 10 K POT
- vero board

Simulate a theft or unauthorized

change in location while the system is armed, the microcontroller detects this discrepancy. Upon detecting unauthorized movement, the microcontroller triggers an alert protocol by activating the GSM module. This module is responsible for sending an alert message to the owner's mobile phone, providing real-time location data of the vehicle and enabling the owner to track it immediately. Concurrently, the LCD may display an alert message, indicating that unauthorized movement has been detected.

The alert message received by the owner on their mobile phone is a critical component of the system, providing the necessary information to take immediate action. This could include contacting law enforcement or using vehicle recovery services. The owner can also disarm the system by entering the correct security code via the keypad or through a remote command, stopping the alert and returning the system to its normal state. When the owner returns to the vehicle and wishes to disarm the system, they enter the security code, which the microcontroller verifies. If the code is correct, the system is disarmed, and the LCD updates to reflect the disarmed status, confirming that the vehicle is now accessible without triggering alerts.

Instruments and Tools

The instruments and tools used in development of this project work include:

- soldering iron
- screw drivers
- pliers
- de-soldering pump
- Multi-meter
- Muiltimeter

The electronic circuit components used includes:

- Arduino UNO

- Integrated circuit
- Load jumper etcetera.

Casing of Anti-theft vehicle security system

In this research work, plastic (Power Bank Case) was employed to enclose the anti-theft vehicle security system in order to hide the identity of the electronic system.

Figure 5: GSM Based Anti-Theft Vehicle Security System

Result and Discussion

Result

This research work title Development and Implementation of a GSM Based Anti-Theft Vehicle Security System consists of a programmable microcontroller, GPS module, and GSM module. The microcontroller processed and coordinated the operation of all the circuit components, GPS module and GSM module. The microcontroller processed the input from the button which verifies the security codes and accurately arming and disarming the system. The button functioned effectively as the primary user interface, allowing the family to enter the security code to arm or disarm the system. The LCD provided clear and immediate feedback to the user, displaying the system's status and any alerts, ensuring easy interaction and monitoring. The GPS modem continuously provided real-time location data, allowing the system to monitor the vehicle's position accurately. The microcontroller successfully detected unauthorized movements based on the GPS data.

The motion sensor accurately detects any unauthorized movement within or around the vehicle, triggering alerts when such activity was identified. The GSM modem reliably sent text messages and calls to the vehicle owner's mobile phone, providing real-time information about the vehicle's location and specific alerts (e.g., unauthorized movement or door opening). The communication between the microcontroller and GSM modem was seamless, ensuring immediate notification to the owner. Upon detecting unauthorized movement or door openings, the system promptly triggered the alert protocol, and a notification was sent to the vehicle owner timely and contained accurate information, enabling swift action to be taken.

Discussion

The GSM Based Anti-Theft Vehicle Security System developed in this project demonstrates a significant advancement in technology. By integrating multiple components the microcontroller, GPS module, button, LCD, and GSM module in the system provides comprehensive and multi-layered approach to preventing vehicle theft events. The microcontroller serves as the central processing unit which coordinates the operations of various components of the electronic system. The microcontroller's ability to process inputs from different sensors and devices ensures that the system can quickly and accurately respond to potential threats of vehicle theft. This coordination is crucial for maintaining real-time monitoring and immediate alert capabilities.

In testing the performance and accuracy of the system, we tested the system severally by changing positions and triggering the button, and of course we received the Google map link of our positions at every point in time. The following locations were detected and the developed GSM based anti-theft vehicle security system:

i. lyekhie girls road, oscar street, Auchi.
ii. Levis filling station opposite school gate campus one
iii. Auchi polytechnic pavilion campus I

This system demonstrated high level of reliability and effectiveness in detecting and responding to potential vehicle theft scenario. The coordinated operation of the microcontroller, sensors, and communication devices ensures that the system can handle various situations, providing robust protection against thefts.

located with the aid of

Conclusion

In this research work, the development and implementation a GSM based anti-theft vehicle security system was properly implemented to track vehicle at various location. The aim is to develop and implement,. After several tests were carried out and programming with different codes, eventually the obliged outcome is put forward. It is a fast, simple, and efficient approach to control and coordinate our home appliances. This electronic system works with a great compelling result.

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SOCIO-ECONOMICS OF SMALL-SCALE MAIZE PRODUCERS IN ETSAKO WEST LOCAL GOVERNMENT, EDO STATE, NIGERIA.

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ABSTRACT

The study analysed the socio-economics of small-scale maize production in Etsako West Local Government, Edo State, Nigeria. The specific objectives explained the socio- economic factors of maize farmers, determine the relationship between the socio-economic factors of small-scale maize farmers' and their income, predict the gender and age in relationship with the annual income per hectare, and recognize the limiting factors faced by the small-scale maize producers. 120 maize producers in the study area were given a questionnaire. Based on the questionnaire responses, the following statistical analyses were carried out: a) descriptive statistics, b) linear multiple regression, and c) gross margin. The study discovered that the most of the respondents (80%) were male and of working age. Also, the most of the respondents were married with five children and own a farm size of 1–2-hectare farm. According to multiple linear regression, females and males between the ages of 21 and 30 are expected to earn ₦150,445.40/ha (345.87 dollars) and ₦150,436.50/ha (345.82 dollars) per year, respectively. On the other hand, as both female and male categories are getting old their expected annual income decreases with 46.82% and 39.65% respectively. According to the findings, it is advised that extension workers should encourage the small-scale maize famers to form cooperative societies in order to gain access to credit, market their produce, acquire farm inputs collectively and solve labour. Furthermore, the state government should provide maize farmers with loans ranging from ₦200,000 (459.77 dollars) to ₦250,000 (574.71 dollars) to assist them in acquiring land for their maize farming business in order to improve food security in the state and throughout Nigeria.

Keywords: small-scale, maize producers, maize, family

INTRODUCTION

Maize is a common food crop that is grown all over the world. According to Food and Agriculture Organization (FAO 2020), it is estimated that the total global maize production in 2020 was 1.05 million thousand tons. And that the United States of America is the world's leading producer of maize. Maize production in the United States of America was 360,252 thousand tons in 2020, accounting for 34.28% of global maize production. As stated by Intergovernmental Panel on Climate Change (IPCC, 2021) maize is typically grown as a food crop in developing countries, but it is also an important component of animal feed in countries such as USA and Brazil. Maize cultivation is common in Africa, as maize is the continent's second most cultivated crop. Also, that maize is unique in that it is mostly grown by smallholder peasant farmers in Africa who lack access to finance and do not have the resources to invest in modern yield development techniques or adaptation options. According to Mgbenka and Mbah, (2016) Small-scale farmers dominate Nigeria agriculture, with maize accounting for the majority of the country's food requirements. Small-scale farmers are defined as those who own less than 10 hectares of land. The study further states that these groups make up about 80% of Nigeria's farming population and are responsible for 80% – 90% production of food in the country and they are the country poorest groups. According to Ayeni, (1991) maize is a very important staple food in Nigeria, and it has grown to be the local 'cash crop,' particularly in the South Western part of the country, where at least 30% of a modest amount of the crop land has been set aside for maize cultivation under various cropping systems. World Atlas, (2017) further stated that in Nigeria maize is one of the most important staple foods and in the world today; maize, rice, and wheat together supply more than half of global caloric intake. Also stated that maize has a caloric supply of about 19.5%, maize (Zea mays L.) is the world's highe lorie supplier. According to Juma, (2010) maize is the third most important cereal in Nigeria, after sorghum and millet.

International Institute of Tropical Agriculture (IITA, 2008) stated that maize is also grown in various parts of the world and is known as the best adapted crop on the world. In FAOSTAT, (2012) recorded that Maize was first introduced to Nigeria in the 16th century and is now the country's fourth most consumed cereal, behind only sorghum, millet, and rice. Sadiq, M.S., Yakassai, M.T., Ahmad, M.M., Lakpene, T.Y., and Abubakar, (2013) revealed that the demand for maize in Nigeria is increasing at a rapid pace every day. Also, that, the demand could be because the grain is used to feed poultry and serves as the primary food source for many families.

Ogunsumi, L.O., Ewuola, S.O. and Daramola, A.G. (2005) observed that Small-scale maize farmers growing maize can improve household hunger, and the increasing effect could double Africa's food production. According to FAO (2017) reported that in 2016/2017, Nigeria produced 10.5 million metric tons of maize. Further confirmed that between 1990 and 2015, Nigeria produced approximately 4.7 million tonnes of maize on average, with the contribution of maize to total grains produced increasing from 8.7% in 1980 to approximately. Also, that maize was planted on approximately 561,397,029 hectares of Nigerian land, accounting for approximately 61% of the country's total cultivable land. According to FAO (2017) maize has the ability to thrive in a variety of environmental conditions (rainfall and dry seasons, low and high temperature, fertile and non-fertile soil, etc), which explains why it is grown in so many different parts of the country. And that there is evidence that maize production in Nigeria is a continuing process.

N:P: K 15:1:5:15 fertilizer is commonly used to cultivate maize in Nigeria, but it is difficult to obtain for maize farmers. Maize farmers use the cultivars Bende white an

ellow, which they purchase from agricultural stations. Mechanization of maize farming is common in large maize farming companies such as Kereksuk Rice Farm in Nasarawa state, Leventis Farm in Agenebode, Edo state, and Obasanjo Farm in Ota, Ogun state. Small-scale maize farmers cannot avoid purchasing or renting machinery.

In his study, Olaiyan, (2015) stated that in Nigeria, users of maize alone and in combination with other food materials included kunu (drink make with maize), akamu (corn custard), tuwo (local powered maize flour) masa (fried maize cake), eko oka (solidified paste make from maize) and igwogho eka (crushed cooked maize like rice).

OBJECTIVES

General Objective

To analysis the socio-economics factors of maize producers of Etsako West Local Government, Edo State, Nigeria.

Sp Specific Objective

i. To explain the socio-economic factors of small-scale maize producers;
ii. To determine the relationship between the socio-economic factors of small-scale maize
iii. producers' and their income;
iv. To predict the gender and age in relationship with the annual income per hectare;
v. To recognize the limiting factors faced by the small-scale maize producers.

MATERIAL AND METHODS

1 Description of Research Location

The study was conducted in Etsako West, one of Edo State's nineteen Local Government Areas. The Local Government Area is in the is in the northern agricultural zone of the State (Edo North). Figure 1 depicts Nigeria in Africa, Figure 1 depicts Edo State

Esako West Local Government. The research site is home to six (6) districts: Auchi, Uzairue, South Ibie, Anwain, Jagbe, and Avhiele. It can be found at latitude 7^{o}31'N and longitude 6^{o}13'E. It has a land area of 946 km^2. According NPC (2006) the research area has a population of 197,609 people. The annual rainfall in the research area ranges between 1500 and 2000mm. The rainfall period is

7 to 8 months, it is a lowland area with fertile sandy loamy soils with less clay and more sand and silt. The research location is agrarian in

rainforest zone and well suited for cultivation of arable crops such as maize, rice, cassava, yam, sorghum, pawpaw, cowpea, iron beans, sw

potato.

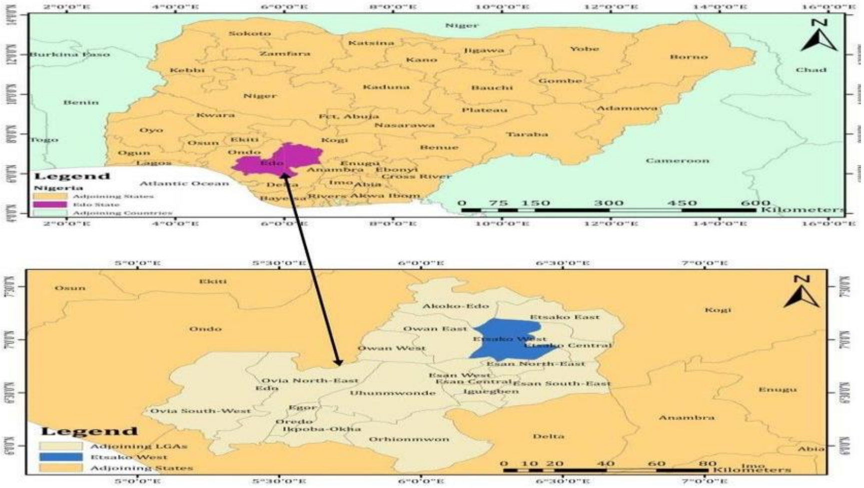

Figure 1 Map of Nigeria showing Edo State and also Etsako West Local Government
Source Researchgate.net

Sample size and sampling technique

The population of this study was small-scale maize farmers in Etsako West Local Government of Edo State, Nigeria. For this study, a two-stage sampling technique was used. In the first stage, two communities with the best maize production were randomly selected from each district to give a total of twelve communities. The second stage involved the random selection of ten small-scale maize farmers from each selected community for answering a questionnaire. At the end, a total of 120 questionnaires were answered.

Data Set

This study used both primary and secondary data. The Primary data was collected with structured questionnaire, which was distributed to the respondents to answer. Data on socio-economic factors and problems were collected with seven questions and 3 questions on maize producers, distribution based on output of maize in kilogram (kg), farm size per hectare (Ha) and annual income in naira (₦) and dollars.

Statistical Analysis

The statistical analysis was divided into three parts. The first analysis is a descriptive analysis that includes frequency counts, percentages, and means for a better understanding of the data set. The second analysis employed multiple linear regression, with annual income as the quantitative dependent variable and socioeconomic characteristics as the independent variables. The third analysis is the calculation of the gross profit and the net farm income of maize production in the study area. For the Multiple Linear Regression, the following model was applied:

$$y = \beta_0 + \beta_1 X_1 + . \quad . \quad . + \beta_n X_n + \epsilon$$ eq. (1) where, for i

=n
observations:
y = annual income (naira/dollar);
$\beta_{1\ to\ n}$ = slope coefficients for each explanatory variable;

β_0= y-intercept (

)

$1\ to\ n$= slope coefficients for each explanatory variable; = the model's error term (also known as the residuals

RESULTS AND DISCUSION

TABLE 1: Respondent summary based on socioeconomic factors (n = 120)

	Variable	Frequency	Percentage
SESSION 1	**AGE**		
	< 20	24	20
	21 – 30	41	34.2
	31 – 40	29	24.2
	41 – 50	20	16.6
	50 and above	6	5
	Average = 30.8 years		
	SEX		
	Male	96	80
	Female	24	20
	MARITAL STATUS		
	Single	41	34.1
	Married	75	62.5
	Divorced	2	1.7
	Widowed	2	1.7
	EXPERIENCE (YEARS)		
	1-5	44	36.7
	6-10	50	41.7
	11-15	12	10
	16-20	5	4.1
	21 and above	9	7.5
	Average = 8.2		
	EDUCATION STATUS		
	Primary	12	10
	Secondary	60	50
	Tertiary	29	24.2
	No formal education	19	15.8
	MEMBERSHIP OF COOPERATIVE SOCIETY		
	Belong	24	20
	Do not belong	96	80

1-5	73	60
HOUSEHOLD SIZE		
6-10	37	30.8
11-15	7	5.9
16 and above	3	2.5
Average = 5.5		
FARM SIZE (ha)		
<1	1	0.8
1-2	70	58.3
3-4	34	28.4
5 and above	15	12.5
Average =3.6 ha		

Section 2 Distribution of maize farmers according to output and farm size

MAIZE OUTPUT RANGE (kg)		
0 – 500	46	38.3
501 – 1,000	15	12.5
1,001 – 1,500	47	39.2
1,501 – 2,000	7	5.8
2,000 and above	5	4.2

Data collection from maize farmers in Etsako West Local, Edo State, Nigeria, (2021) Thirty-four-point two percent (34.2%) of the respondents were between the age brackets 21-30 years, 24.2% were between 31-40years, 20% of the respondents were not more than 20years, 16.6% were between 41-50 years while only 5% of the respondents were above 50 years. The average range of the respondents was 30 years. This implies that the maize farmers in this area are very youthful and can supply an excellent amount of labour

open to innovation and creativity. This is also like the findings of Zongoma, Et al, (2015), that the age between 21 - 40 year are in their active age and because maize farming is a strenuous activity.The gender distribution of the respondents reveals that the majority (80%) were male, while the female counterpart was (20%). This is consistent with the findings of Alimba and Igberi (2005), who found that gender influences production of maize.

education). According to Amaz(2000), farmers' efficiency in using information on new production techniques increases

According to Table 1, a large proportion (62.5%) of the small-scale maize farmers were married, while 34.1% were single; 1.7% were divorced, while 1.7% were widowed. According to Girei A.A. et al. (2018), married farmers may be more dedicated and ave a greater imperative for higher productivity to meet family demands for food and income, among other things.

According to the distribution of respondents based on highest educational qualification obtained, 50% had secondary education, 10% had primary education, 24.2% had tertiary education and 15.8% had no formal education. This demonstrates that the most of the farmers (84.0%) had some form of formal education (primary school, secondary school and tertiary

with education, as does their productivity.

According to the distribution of respondents based on farming experience, the most of the maize farmers (41.7%) have farming experience between 6 - 10 years, 36.7% have 1 - 5 years of farming experience, 10% have 11 - 15 farming experience, and 4.1% have 16 - 20 farming experience (Fig. 8). This implies that years of farming experience influence maize output and annual income as they make use of the skills acquired to improve their maize production. Apata (2010), research finding, stated that farming years of experience can improve maize famers production.

According to the distribution of respondents by household, the majority (60.8%) of farmers had families of one to five people, while 6 – 10 (30.8%), 11 – 15 (5.9%) and 16-20) (2.5%). This agrees with the findings of Sadiq *et al.* (2013) who noted that the majority (70%) of the respondents have a household size ranging from 1-10 persons. This is consistent with the findings of Ozor and Cynthia (2010), who discovered that a larger family size implies more family labour for household farm activities.

Multiple linear regression

The relationship between some economic factors (such as age, marital status, sex, education, farm size, farming experience, family size, used labour and annual income) and the annual income/ha of the respondents was determined using the regression analysis. The end model is presented below:

Y_ij=intercept+
Factors+MAIZEOUTPUT.
FARM.SIZE+FARM.SIZE.HOUSEHOLD.SIZE+ ϵij (eq.5)

With i =1, 2, ...,10, j = 1,2...,ji, ϵij = independent random variable with normal distributionThe ANOVA of multiple regression linear model is showed at Table 2. Output of the multiple linear regression.

Table 2

Variables	Coefficients:	Estimate	Std. Error	t value	Pr(>|t|)	Level of ificance
Intercept	AGE.CLASS IALE 11-20	-83155.66	16404.29	-5.069	1.73e-06	***
Factors	21-30	88461.67	13032.55	6.788	6.99e-10	***
	31-40	77131.18	14757.87	5.226	8.84e-07	***
	41-50	86060.81	20224.21	4.255	4.55e-05	***
	51-70	83968.99	25361.72	3.311	0.001276	**
	AGE.CLASALM 11-20	44402.96	12370.31	3.589	0.000505	***
	21-30	94707.69	11613.84	8.155	8.01e-13	***
	31-40	82374.34	13022.52	6.326	6.29e-09	***
	41-50	95344.51	13750.61	6.934	3.45e-10	***
	51-70	83529.89	16990.75	4.916	3.27e-06	***
	MAIZE.OUTPUT. M.SIZE	201.80	20.69	9.752	< 2e-16	***
Variable inuing	FARM.SIZE.HOU IOLD.SIZE	77502.82	5705.86	13.583	< 2e-16	***

*** = Significant at 0.001; Multiple R-squared: 0.9522, Adjusted R-squared: 0.9487; F-statistic: 271.4z

The annual income predicted by the multiple regression linear model (eq. 5) is shown in Table 3.

Table 3 Annual income predicted by multiple linear regression model in dollars and naira/

	(Dollar/ha)		
Female 11-20	232.19	101,001.40	67.14
21-30	345.85	150,445.40	100
31-40	183.91	80,000.71	53.18
41-50	128.16	55,750.55	37.06
51-70	101.15	44,000.47	29.25
Male 11-20	10.19	4,434.43	2.95
21-30	345.83	150,436.50	99.99
31-40	208.73	90,796.20	60.35
41-50	203.10	88,344.53	58.72
51-70	98.39	42,800.46	28.45

According to the results of the multiple regression linear model, there was an interaction between age and gender (table 2). As shown in table 3, it allowed us to create gender and age groups. Females aged 11 to 20 can expect to earn N101,001.40/ha (232.19 dollars/ha) in annual maize sales. Females aged 21 to 30 years, on the other hand, earn N150,445.40/ha (345.85 dollars/ha) more in annual earnings. Furthermore, females between the ages of 31 and 40 are expected to earn N80,000.71/ha (183.91 dollars/ha) per year. Females aged 41 to 50 are expected to earn N55,750.55/ha (128.16 dollars/ha) per year. Females aged 51 to 70 will receive N44,000.47/ha (101.15 dollars/ha) per year. This is because the females are young and have a lot of energy for maize faming activities.

Male counterparts aged 11 to 20 are expected to earn N4,434.43/ha (10.19 dollars/ha) in maize sales per year. Furthermore, males aged 21 to 30 are expected to earn N150,436.50/ha345.83 dollars/ha) per year. Males aged 31 to 40 are expected to earn N90,796.20 (208.73 dollars/ha) per year. Males aged 41 to 50, on the other hand, can expect to earn N88,344.53/ha 203.10 dollars/ha) per year. Furthermore, males aged 51 to 70 are expected to earn N42,800.40/ha (98.39 dollars/ha) per year. Males aged 20 to 30 years earn the highest annual income (N150,436.50/ha. (345.83 dollars/ha)) in this report, as do females. This finding agrees with the findings of Zongoma, Et al, (2015), that the age between 21 - 40 year are in their active age and because maize farming is a strenuous ac

problems of small-scale maize producer

Table 5 Problems facing small-scale maize producers in the research location.

Problems	Number of **Responses**	Percentage	Ranking
High labour cost	87	72.5	1st
Pest and diseases	82	68.3	2nd
Insufficient capital	74	61.7	3rd
Insufficient storage facilities	72	60.0	4th
Marketing problem	69	57.5	5th
Transportation problem	68	56.7	6th
Limited credit facilities	60	50.0	7th
Expensive inputs	55	45.8	8th
Insufficient agricultural Information	45	37.5	9th
Pilfering	42	35.0	10th
Labour exchange	28	23.3	11th
Sharing cropping problem	27	22.5	12th

Data collection from maize farmers in Etsako West Local, Edo State, Nigeria, (2021)

The distribution of respondents based on maize cultivation issues is depicted in Table 5. The vast majority of respondents agreed that high labour costs, pests and diseases, insufficient storage facilities, insufficient capital, marketing issues, transportation issues, limited access to credit, and high input costs were the major impediments to their production activities. According to Adesiyan (2015), the most serious problems

maize production were high labour costs, insufficient funding, and high transportatio

FINAL CONSIDERATIONS

Based on the outcome of the research, it is recommended that:

i. The state government should provide maize farmers with loans ranging from ₦200,000 (459.77 dollars) to ₦250,000 (574.71 dollars) to assist them in acquiring land for their maize farming business in order to improve food security in the state and throughout Nigeria.

ii. Federal Government should provide farm inputs at reduced prices to maize farmers at the beginning of cultivation period.

iii. Extension agents should encourage the small-scale maize famers to form cooperative societies in order to gain access to credit, market their produce and acquire farm inputs collectively.

iv. Farmers should be properly be educated on pest and disease control measures by extension agents.

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A Geospatial Information System (GIS) for Integrated Campus Asset and Environmental Management: A Case Study of Auchi Polytechnic, Campus 1.

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ABSTRACT

Rapid infrastructural growth at Auchi Polytechnic, Campus 1 (Edo State, Nigeria) has outpaced available topographic mapping, which previously covered mainly built-up areas, creating a need for an integrated Topographic Information System (TIS) to support campus asset and environmental management. This study aimed to develop an up-to-date geospatial database and terrain products that quantify topographic variation, enable querying of campus features, and inform sustainable development and flood-risk-sensitive planning. Primary spatial data were acquired through GNSS observations using a Hi-Target DGPS Rover in Real-Time Kinematic (RTK) mode with a CORS reference station; boundary control comprised 21 perimeter points and multiple campus feature points with associated attributes. Secondary datasets included 30 m SRTM DEM and high-resolution satellite imagery accessed via Google Earth Pro/QuickMapServices. Data processing and spatial analyses were implemented using ArcGIS Pro (including raster clipping, raster-to-point spot height generation, DEM-based surface analysis, reclassification, overlay, and database querying), QGIS 3.38 (basemap integration, digitizing and vector layer creation), Surfer 20 (3D surface and wireframe visualization; gridding via interpolation such as Kriging/IDW), and AutoCAD (perimeter plotting). The resulting TIS produced a clipped DEM and derivative topographic outputs including TIN, contour representation, slope and aspect maps, 3D surface and wireframe models, and an elevation map reclassified into low, medium, and high zones; overlay and single-criterion queries linked buildings to elevation classes and also differentiated old versus newly constructed buildings, supporting identification of structures potentially susceptible to flooding in low-lying areas. Overall, the integrated TIS demonstrates the value of combining GNSS, remote sensing, and GIS database design for data-driven campus planning, and underscores the need for regular database updates, improved connectivity and computing capacity, and sustained training and inter-departmental collaboration to institutionalize geospatial decision support.

Key word; Geographic Information System ,Surveying,- Environmental Management. *Remote Sensing;* ArcGIS; QGIS; Sur*f*

INTRODUCTION

Surveying is instrumental in driving successful land development, providing essential spatial insights for infrastructure planning, urban management, and environmental stewardship, built upon the cornerstone of topographic surveying. Leveraging advancements in technology. Topographic information system (TIS) is a computer-based platform designed to collect, store, process, analyze, and disseminate topographic data. This technology facilitates the management and visualization of complex spatial data, empowering professional to make informed decisions in various fields. The integration of topographic surveying with Geographic Information Systems (GIS) has ushered in a new era of data-driven decision-making in environmental management. TIS and GIS are powerful geospatial technologies that enable accurate mapping, analysis, and decision-making. TIS not only facilitates the collection and analysis of topographic information but also provides a structured framework for storing, processing, and visualizing spatial data about the earth's surface Adewara, (2017). *Lie et al* (2019), Topographic information systems (TIS) integrate surveying, geographic information system (GIS), remote sensing and photogrammetry to create digital model of the earth's surface. This research work aims at creating a Topographic Information System for Auchi Polytechnic, Auchi, Edo State, Nigeria, which has undergone rapid development and the existing topographical map cover only the built-up area. So, there is need to produce a complete topographic information system based on the existing topographical data in order to determine the topographic variation of the land surface, to ensure effective socio-economic development and produce an updated map. It is also imperative that a comprehensive database be created, which will serve as a source of information for future development and environmental management. Locational and attribute data of features will be collected for the study area, and the processing of this data will be done using multiple software such as QGIS 3.38, Surfer 20, and ArcGIS Pro 2.8. A database will also be created to relate both spatial data and attribute data and maps such as Topographic Map, hydrologic model, Digital Terrain Models (DTM), Elevation Map, and Slope Map to be produced Ojiako and Jimoh, (2017) employed a Total Station (South S74301) for ground survey methods, including traversing, detailing, and simultaneous spot height measurements, to gather geometric (spatial) data for the creation of a Topographic Information System (TIS) at the Federal School of Surveying, Oyo which covered an area of about 33.226 hectares. The data processing involved tools like Leica Geo Office Tools, South NTS Software, Notepad, and Microsoft Excel for downloading, editing, and preprocessing. AutoCAD 2016 was used for droughting, Surfer 11 for generating Digital Terrain Model (DTM) and 3D Wireframe Maps, while ArcGIS 10.0 facilitated spatial analysis, query generation, and information presentation. The structured model database in a relational table format was created to support decision- making policies for professionals in land surveying, architecture, engineering, and urban and regional planning. This TIS is recommended as a permanent tool for effective and sustainable development. Oluwole and Ajibade, (2021) conducted a topographic survey in Ibadan, Nigeria, focusing on improving the accuracy of existing topographic maps. They used tools like Total Stations, GPS, and Unmanned Aerial Vehicles (UAVs) to gather data. The study employed software such as ArcGIS, AutoCAD, and Surfer for data processing. The end product included Topographic, Contour, and Elevation maps, as well as a comprehensive GIS database. The maps produced were used for flood risk assessment and urban land-use planning. Adegboye (2019) performed a study in Lagos, Nigeria, aimed at updating the city's outdated topographic maps. They collected data using a combination of GPS, Total Stations, and aerial imagery from drones. The data was processed using AutoCAD, ArcGIS, and Global Mapper software. The end product consisted of a series of Topographic and Contour maps, as well as a comprehensive Geographic Information System (GIS) database for urban planning. The maps were particularly used for road construction and drainage planning.

Adewara, (2017) conducted a study focused on addressing the inadequacies in th west campus of the Federal Polytechnic Ilaro (FPI) in South West

Nigeria, covering an area of 5 hectares. This region faced challenges such as insufficient walkways and drainage systems, prompting the need for a Topographic Information System (TIS) as a decision-making tool for effective facility management and flood-related concerns. The planning stage involved using a Landsat 8 (2010) image to gain a general overview of the 5-hectare project site. Field data, collected with a Total Station instrument, underwent processing in Microsoft Excel and was imported into AutoCAD Civil 3D 2013 for scripting and generating a surface contour. Topographic Information System (TIS) was established in a computer-based system, including the creation of a Digital Terrain Model (DTM) for further analysis using ArcGIS 10.2 and Surfer 10 software. The resulting TIS allows for versatile manipulations and querying, demonstrating its crucial role in supporting physical planning, accurate decision-making, and efficient environmental management processes. Akpan and Eze, (2018) conducted a study in Port Harcourt, Nigeria, focusing on the development of a topographic information system to assess flood risks. The researchers employed LiDAR technology, combined with GPS surveys, to collect high-precision elevation data. Using software tools like ArcGIS and Global Mapper, they produced detailed topographic

maps and Digital Elevation Models (DEMs) that depicted the flood-prone areas of the city. The end product was a series of flood risk maps that were used by local authorities to plan mitigation measures and enhance the city's disaster preparedness strategies. The study demonstrated the critical role of topographic information in addressing environmental challenges and improving urban resilience.

Awange and Ong'ang'a, (2005) conducted a study focusing on the Lake Victoria Basin in Kenya. Their objective was to develop a detailed topographic information system that could be used for environmental monitoring and resource management. They employed Geographic Information System (GIS) technologies along with Digital Elevation Models (DEMs) and satellite imagery. The use of GIS software such as ERDAS Imagine and ArcGIS enabled them to create high-resolution maps that depicted elevation, slope, and aspect. The study's end product was a set of topographic maps that were instrumental in analyzing land cover changes and assessing soil erosion risks. The maps were used by environmental agencies and local communities for sustainable land use planning and disaster management.

In a study aimed at supporting agricultural development, Saka and Bello, (2010) carried out a topographic survey in the Sokoto State region of Northern Nigeria. They used Digital Theodolites and GPS equipment to map the topography of the area, focusing on the identification of suitable land for irrigation projects. Data collected from field surveys was processed using Surfer 10 and AutoCAD software to generate digital topographic maps with detailed contour lines. The maps produced served as a basis for planning new irrigation systems and optimizing the allocation of agricultural resources. The study highlighted the importance of accurate topographic information in enhancing agricultural productivity and mitigating the impacts of flooding. Dawod and Al-Ghamdi, (2017) conducted a study in Al Majmaah City, Saudi Arabia, employing Geographic Information System (GIS) technology to update surveying maps for the Majmaah Merqeb area.

METHODOLOGY

The technical methodology and

procedural framework adopted for the design and implementation of the Topographic Information System (TIS) within the study area, is as presented in the flowchart provided below: This offers a visual representation of the research's workflow and execution phase

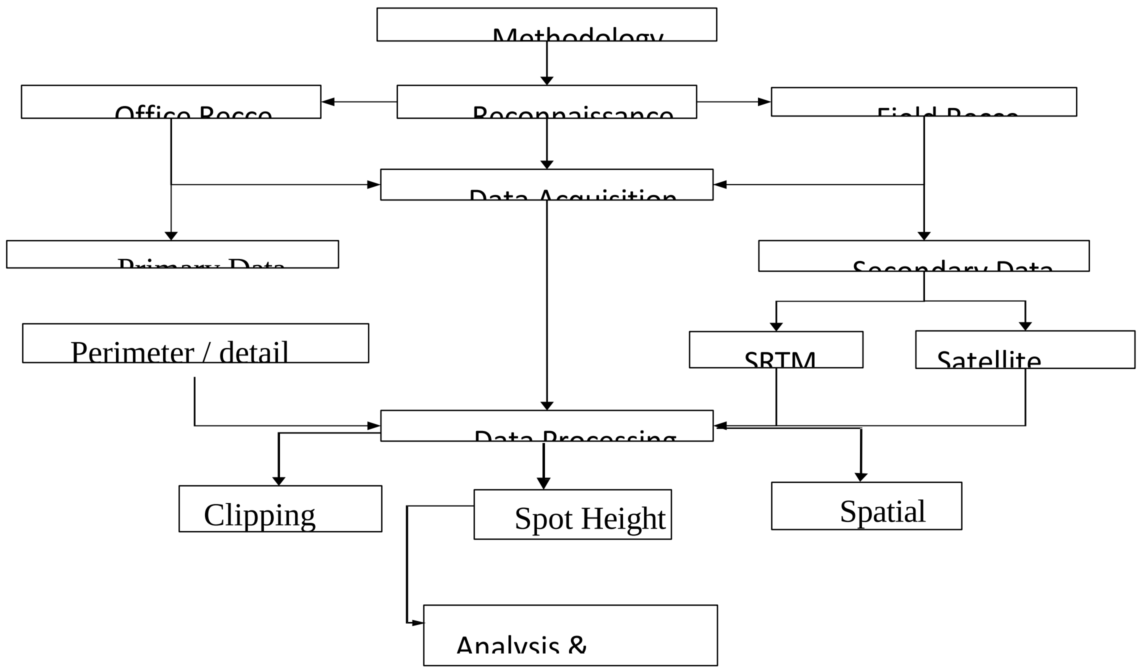


Fig 1*: Cartographic Model* (Source: Author's field work)

RECONNAISSANCE

Reconnaissance is the first step in surveying, involving a preliminary examination of the area to gather information and plan the survey. It helps surveyors understand the terrain, natural features, and potential challenges, enabling them to create an effective and efficient survey plan. There are two types of reconnaissance surveys which are the office and field reconnaissance.

OFFICE RECONNAISSANCE

In surveying, office reconnaissance refers to the phase of survey planning and preparation that takes place in the office, typically before the fieldwork begins. During office reconnaissance, surveyors gather and analyze existing

as maps, satellite imagery, previous survey records, and any available data that can aid in planning the field survey.

FIELD RECONNAISSANCE

Field reconnaissance is the direct contact with the project site for investigation and it gives more details of the landform and other structures that are over the ground which may form an obstacle. This involves visiting the site to locate existing pillars on the ground and a sketch of the project site was produced. Also, a recce diagram was drawn.

EQUIPMENT AND MATERIAL USED

This includes both the hardware and software that was used for data collection management and

Hardware requirement includes

Hi-Target DGPS Rover and its accessories

1. Laptop (HP Steam 11, 4 RAM, 32GB SSD)

2. Airtel 5G broadband router

3. field book/Pen

4. Printer HP LaserJet P2201 Series

Software requirement includes

1. ArcGIS Pro

2. ArcMap 10.7

3. QGIS 3.38

4. Microsoft Office 2019

5. Microsoft Excel 2019

6. Google Earth Pro for downloading of high-resolution satellite imagery

DATA ACQUISITION

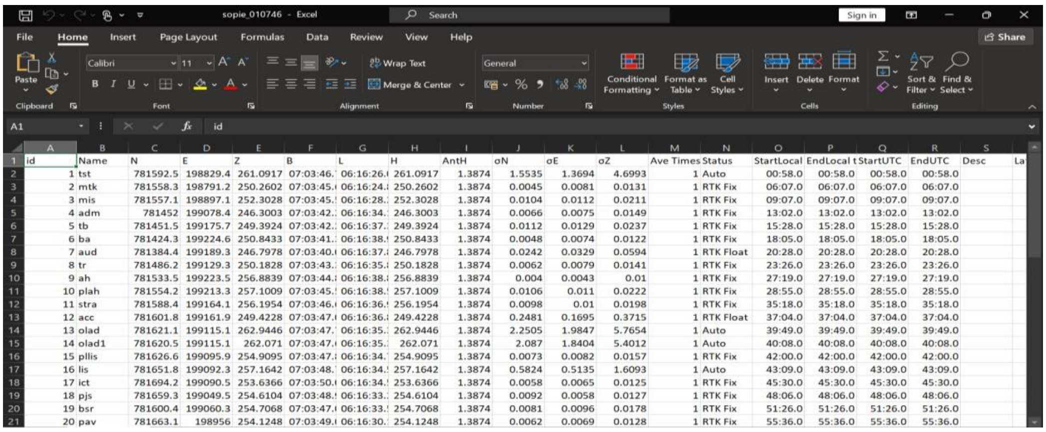
This refers to the process of gathering, collecting and recording data from various sources, sensors, or instruments. It involves the capture of raw data, which was processed, analyzed, and transformed into useful information. There are two types of data acquisition primary and secondary data.

PRIMARY DATA

Primary data refers to original, firsthand information collected directly from the source. The primary was collected through GNSS observation. There are different modes of GNSS observation e.g.: static, RTK and PPK. Real time kinematic mode was used whilst using a CORS as the reference station.

PERIMETER AND DETAIL SURVEY

After checking the GPS receiver, start the perimeter survey by connecting it to the CORS station for RTK corrections. First, take the receiver out, insert the battery, attach the tracking rod, and power it on. Then, turn on the data logger, open the app library, and launch "Hi-Survey." Create a new folder, set the coordinate system to UTM-WGS84 Zone 32N, return to the main menu, select Devices, choose the receiver's serial number, and connect. Next, connect to the CORS station, go back to the main menu, and click the Detail Survey icon to begin surveying. When finished, export the data to your laptop, then disconnect and shut down the receiver



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5	tb	781451.5	199175.7	249.3924	07:03:42.	06:16:37.	249.3924	1.3874	0.0112	0.0129	0.0237	1	RTK Fix	15:28.0	15:28.0	15:28.0	15:28.0		
6	ba	781424.3	199224.6	250.8433	07:03:41.	06:16:38.	250.8433	1.3874	0.0048	0.0074	0.0122	1	RTK Fix	18:05.0	18:05.0	18:05.0	18:05.0		
7	aud	781384.4	199189.3	246.7978	07:03:40.	06:16:37.	246.7978	1.3874	0.0242	0.0329	0.0594	1	RTK Float	20:28.0	20:28.0	20:28.0	20:28.0		
8	tr	781486.2	199129.3	250.1828	07:03:43.	06:16:35.	250.1828	1.3874	0.0062	0.0079	0.0141	1	RTK Fix	23:26.0	23:26.0	23:26.0	23:26.0		
9	ah	781533.5	199223.5	256.8839	07:03:44.	06:16:38.	256.8839	1.3874	0.004	0.0043	0.01	1	RTK Fix	27:19.0	27:19.0	27:19.0	27:19.0		
10	plah	781554.2	199213.3	257.1009	07:03:45.	06:16:38.	257.1009	1.3874	0.0106	0.011	0.0222	1	RTK Fix	28:55.0	28:55.0	28:55.0	28:55.0		
11	stra	781588.4	199164.1	256.1954	07:03:46.	06:16:36.	256.1954	1.3874	0.0098	0.01	0.0198	1	RTK Fix	35:18.0	35:18.0	35:18.0	35:18.0		
12	acc	781601.8	199161.9	249.4228	07:03:47.	06:16:36.	249.4228	1.3874	0.2481	0.1695	0.3715	1	RTK Float	37:04.0	37:04.0	37:04.0	37:04.0		
13	olad	781621.1	199115.1	262.9446	07:03:47.	06:16:35.	262.9446	1.3874	2.2505	1.9847	5.7654	1	Auto	39:49.0	39:49.0	39:49.0	39:49.0		
14	olad1	781620.5	199115.1	262.071	07:03:47.	06:16:35.	262.071	1.3874	2.087	1.8404	5.4012	1	Auto	40:08.0	40:08.0	40:08.0	40:08.0		
15	pllis	781626.6	199095.9	254.9095	07:03:47.	06:16:34.	254.9095	1.3874	0.0073	0.0082	0.0157	1	RTK Fix	42:00.0	42:00.0	42:00.0	42:00.0		
16	lis	781651.8	199092.3	257.1642	07:03:48.	06:16:34.	257.1642	1.3874	0.5824	0.5135	1.6093	1	Auto	43:09.0	43:09.0	43:09.0	43:09.0		
17	ict	781694.2	199090.5	253.6366	07:03:50.	06:16:34.	253.6366	1.3874	0.0058	0.0065	0.0125	1	RTK Fix	45:30.0	45:30.0	45:30.0	45:30.0		
18	pjs	781659.3	199049.5	254.6104	07:03:48.	06:16:33.	254.6104	1.3874	0.0092	0.0058	0.0127	1	RTK Fix	48:06.0	48:06.0	48:06.0	48:06.0		
19	bsr	781600.4	199060.3	254.7068	07:03:47.	06:16:33.	254.7068	1.3874	0.0081	0.0096	0.0178	1	RTK Fix	51:26.0	51:26.0	51:26.0	51:26.0		
20	pav	781663.1	198956	254.1248	07:03:49.	06:16:30.	254.1248	1.3874	0.0062	0.0069	0.0128	1	RTK Fix	55:36.0	55:36.0	55:36.0	55:36.0		

Name	Northings	Eastings
APB01	199296.8	781587.73
APB02	199275.21	781380.12
APB03	199250.15	781379.84
APB04	199229.58	781340.67
APB05	199208	781284.15
APB06	198198.94	781583.1
APB07	198231.66	781683.96
APB08	198230.16	781692.49
APB09	198234.26	781708.52
APB10	198263.58	781697.38
APB11	198282.77	781745.52
APB12	198229	781752
APB13	198231.83	781885.08
APB14	198446.91	781857.78
APB15	198760.43	781875.26
APB16	198833.53	781866.58
APB17	198834.93	781871.89
APB18	198852.76	781865.36
APB19	199119.05	781843.35
APB20	199200.41	781650.61
APB21	199293.6	781647.68

Point Name	Northings	Eastings
Tst	781592.5	198829.4
Mtk	781558.3	198791.2
Mis	781557.1	198897.1
Adm	781452	199078.4
Tb	781451.5	199175.7
Ba	781424.3	199224.6
Aud	781384.4	199189.3
Tr	781486.2	199129.3
Ah	781533.5	199223.5
Plah	781554.2	199213.3
Stra	781588.4	199164.1
Acc	781601.8	199161.9
Olad	781621.1	199115.1
olad1	781620.5	199115.1
Pllis	781626.6	199095.9
Lis	781651.8	199092.3
Ict	781694.2	199090.5
Pjs	781659.3	199049.5
Bsr	781600.4	199060.3

SECONDARY DATA

Secondary data refers to existing information that has been previously collected, processed, and published by others. The secondary data was obtained from online repositories listed in the table below:

Table 3: Secondary dataset and their source

S/N	Data type	Description	Source
1	SRTM	DEM (30m) Resolution	https://search.earthdata.nasa.gov/
2	Satellite imagery	Base map of study area	QuickMapServices

CREATION OF DIGITAL ELEVATION MODEL (DEM) DATA

The SRTM DEM is a global digital elevation model created from radar data collected during the 2000 Shuttle Radar Topography Mission. It has a spatial resolution of 30 meters (90 meters for global data) and vertical accuracy of 5-10 meters. To download it, visit the Earth Explorer website (https://search.earthdata.nasa.gov/), sign in or create an account, then go to the "Data Sets" tab. Select "Digital Elevation" under "Data Categories" and choose SRTM or another DEM. Define your search area by coordinates, place name, bounding box, or shapefile, then click "Search." Review the results, select the dataset, check details, choose a download format like GeoTIFF or HGT, and click "Download." The download time depends on dataset size.

DATABASE DESIGN

A database is an organized collection of structured information, or data, typically stored electronically in a computer system. The data is often made up of alphanumeric characters, punctuation, and encoded graphics, usually structured as tables, queries, reports, forms and macros. This is the heart of GIS and the process of designing a spatial database is known as the modeling of real-world entities and their interrelationship. They are analyzed and modeled in the world solving problems using the maximum amount of data.

DATABASE DESIGN PHASES

Data modelling is the process by which the real-world entities and their relationship are analyzed and modeled in such a way maximum amount of data, care have to be exercised here as improper and lost cost recovery. In obtaining a GIS database, there are two main phases. These are the design phase and construction or implementation phase. See figure below:

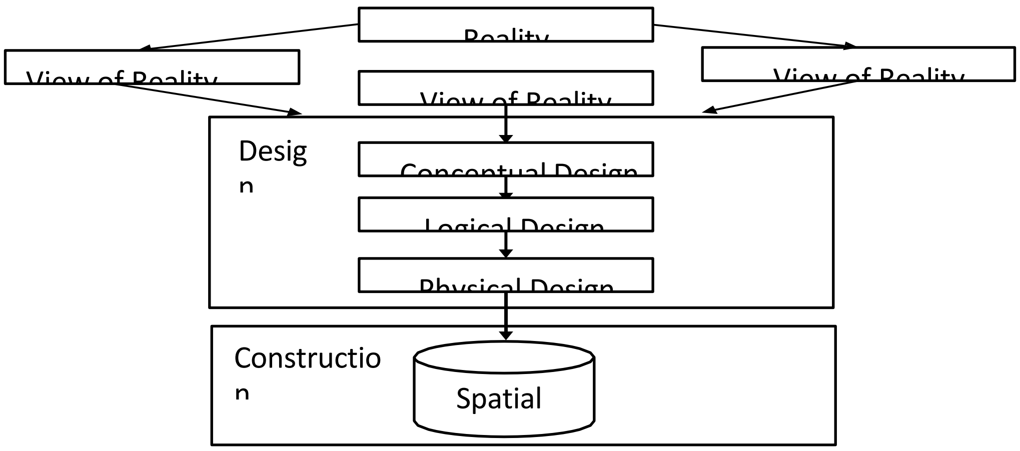


*Fig 2.: Design and Construction Phases of Spatial Database (*Source: Kufoniyi,1998)

The design phase (data modeling) backed up by reality as basis, consist of three levels namely:

1. Conceptual design phase
2. Logical design phase
3. Physical design phase

CONCEPTUAL DESIGN

This means an arrangement/presentation of a human conceptualization of reality. How humans see the world. That is the representation of human conceptualization of reality. Here we must decide how the

view of reality will be presented in a simplified manner but still satisfy the information requirement of the organization concern

OGICAL DESIGN (DATA STRUCTURE)

The process of logical design involves arranging data into a series of logical relationships called entities and attributes. A representation of the data model, designed to reflect the recording of the data in computer system is called logical design of data or data structure. Popular data structures that one might choose from include relational (as used in INFOCAM), geo-relational (as in ARC/INFO), network, hierarchic, object-oriented (as in SMALL WORLD and ONTOS) and object-relational (as in ILLUSTRA).

PHYSICAL DESIGN

During physical design, you transform the entities into tables, the instances into rows, and the attributes into columns. Physical design is the stage of the design process that follows logical design. It involves creating a detailed, concrete representation of the system or project, focusing on the specific technologies, implementations that will be used. materials, and the

representation of the data structure in the

format of the implementation software is usually done at the beginning of the database creation phase. For example, using Dbase-IV SQL mode, we would translate the generic relational structure into dbase.

SPATIAL DATABASE

A spatial database is a database optimized for storing and querying data that represents objects defined in a geometric space. Most spatial databases allow the representation of simple geometric objects such as points, lines and polygons. It is used to store and query data that represents object in geometric space. It consists of structured spatial data, based on vector tessellation or object-oriented data model and implemented by relational, network, hierarchic, object-oriented or object-relational data

EODATABASE CREATION IN ARCGIS PRO

A file geodatabase in ArcGIS stores spatial and attribute data in a single folder with a ".gdb" extension. To create one in ArcGIS Pro, go to the Databases tab, click "New Geodatabase," select "File Geodatabase," choose a save location, enter a name, and click "Ok" to

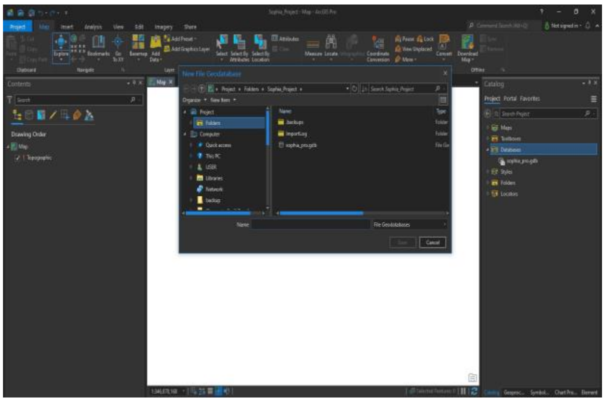


Fig 3: File Geodatabase creation using ArcGIS Pro

ADDING BASE MAP IN QGIS

In QGIS, adding base maps is essential for digitizing and analysis. For this project, the QuickMapServices plugin was used to add a Google Satellite base map, which avoids errors from manual georeferencing and ensures accurate spatial alignment. To add it, install the plugin via Plugins > Manage and Install Plugins, search for QuickMapServices, and install it. Then, go to the Web menu, select Quick MapS ervices > Google Satellite, and the base map will appear on the map canvas for high-resolution visualization

FEATURE DIGITIZATION

This process converts maps or images into digital vectors by tracing features like buildings. In QGIS, create a new GeoPackage layer via Layer > Create Layer > New Geo Package Layer. Set the database name, table name (e.g., Building), geometry type as polygon, and CRS to WGS84/UTM zone 32N. Add building attributes under "New Field" and click OK. The data is then imported into ArcGIS Pro and saved in a File Geo data base.

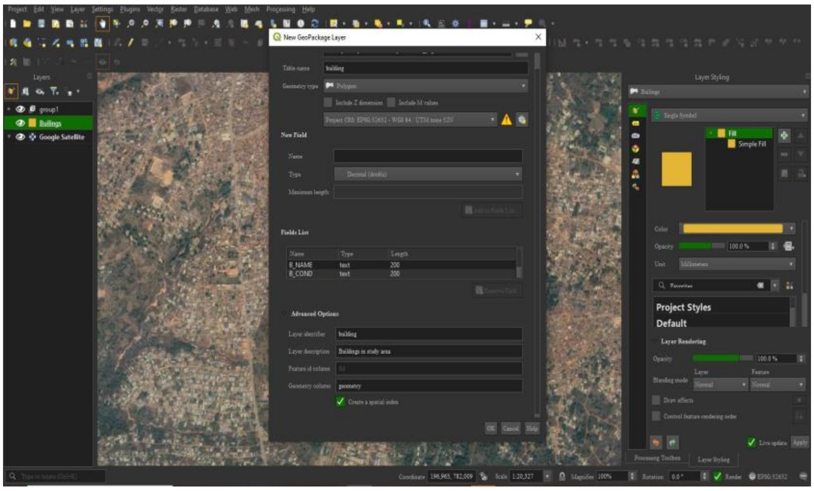


Fig .4.: Creating New Layer

DATA PROCESSING AND ANALYSIS

This chapter focuses on processing the acquired data, and conducting spatial analysis.

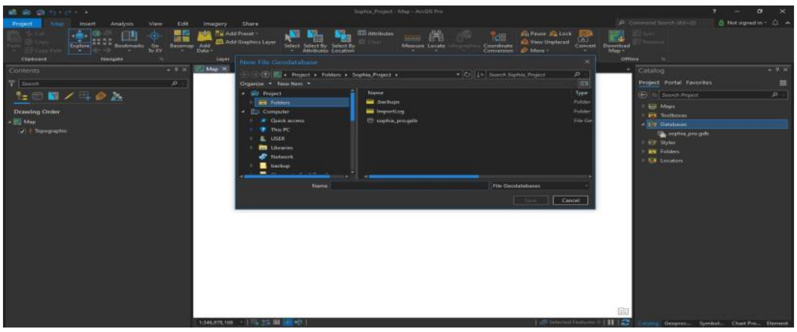
DATA PROCESSING

PLOTTING BOUNDARY POINT IN AUTOCAD

Plotting in AutoCAD can vary by user, but the method used involve several key steps. First, launch AutoCAD and open an existing DXF file. Then zoom to the extents of the drawing to view the full layout. Next, set the drawing

This involves using multiple geospatial technique and tools to process the DEM for analysis. e.g plotting boundary in AutoCAD, generating spot height, interpolation, clipping to boundary extent etc.

units by typing UN, and adjust parameters such as decimal precision, angular type (Degrees/Minutes), and set the units to meters, ensuring the direction is set to North with the clockwise option ticked. For perimeter plotting, go to the Tools menu, select Run, choose



the relevant file to import, and press Enter. Finally, input the bearing, distances, and station IDs to complete the plotting which generated the perimeter of the study area as in figure 6

CLIPPING DEM TO BOUNDARY EXTENT

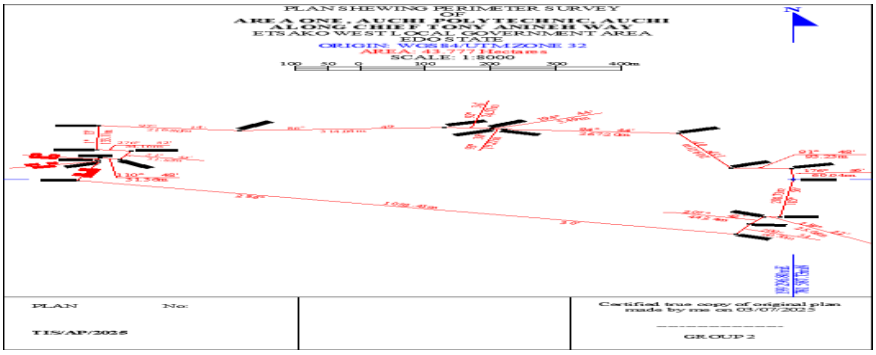


Fig 6.: Perimeter plan of study area

The downloaded DEM extended beyond the project boundary. To clip it in ArcGIS Pro, load both the raster and boundary file. Go to Analysis → Tools, search for Clip Raster, and open the tool. Set the Input Raster, define the clipping boundary, name the Output Raster, and check "Use Input Features for Clipping Geometry" if using a polygon. Click Run to generate the clipped raster.

GENERATING SPOT HEIGHT AND EXTRACTING HEIGHT DATA FROM DEM

A grid of random points was created within the project area using the raster to point tool in ArcGIS Pro to ensure even spatial distribution for accurate topographic analysis. Elevation data was then extracted from the SRTM DEM for each point to assess the terrain. The process begins by adding the project boundary file to the map canvas. Next, open the Geoprocessing tab, search for and select raster to point and set the output location. To extract coordinates in ArcGIS Pro, open the Attribute Table, click Calculate Field, set the input table to the spot height layer, and choose field X or Y. Set expression type to Arcade, and enter Geometry($feature).x for Eastings or Geometry($feature).y for Northings. Validate with the green check, then click Apply and Ok.

RESULTS AND DISCUSSION

The results and discussion of the research are as illustrated in fig 3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 3.7, 3.8, 3.9, 3.10, 3.11a, 3.11b, 3.11c, 3.12a, 3.12b, and table 3.1 respectively at the stated pagesbel

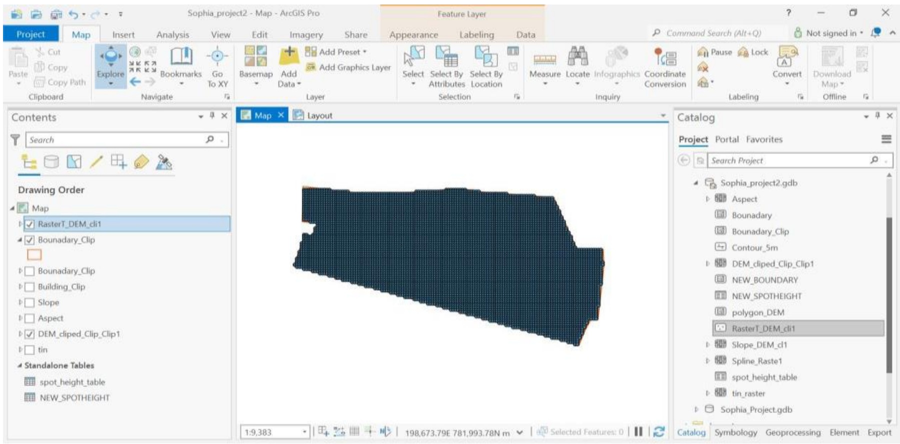


Fig 7.: Spot Height Creation

SPATIAL ANALYSIS

Spatial analysis in a Topographic Information System (TIS) involves using GIS tools to interpret elevation and terrain data for understanding landforms and slopes. It begins with acquiring topographic data from sources like DEMs or surveys, followed by geoprocessing techniques such as interpolation to create continuous elevation surfaces. Slope and aspect analysis help assess land steepness and direction, essential for erosion control, construction, and farming. Contour mapping visualizes elevation changes.

TRIANGULATED IRREGULAR NETWORK

This analysis shows the triangulated Irregular Network (TIN) of Ares One, Auchi Polytechnic, Auchi. The TIN provides the elevation model of the study area. It is also the basis for other analysis such as contour, aspect, slope etc. as in figure 8.

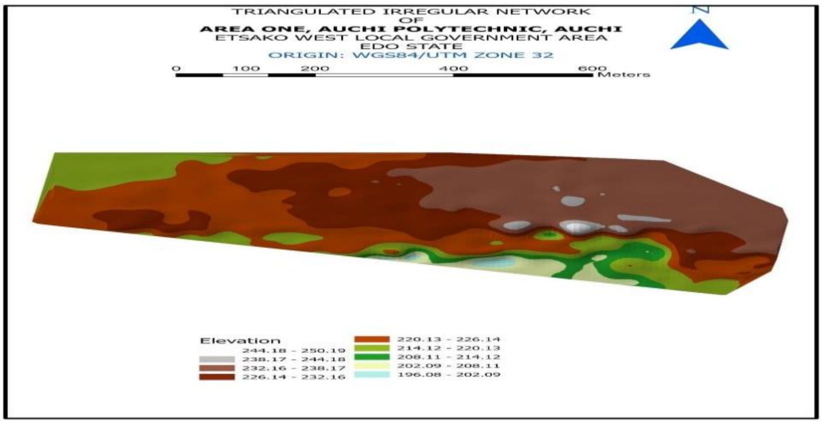


Fig. 8: Triangulated Irregular Network (TIN) of the study area.

CONTOUR MAP

A contour map represents elevation using lines that connect points of equal height, helping visualize terrain shape and slope. To create one in ArcGIS Pro, add your DEM via Map → Add Data. Then, go to Analysis → Tools, search for Contour under Spatial Analyst Tools

→ Surface. Set the Input Raster to your DEM, define the Output Feature Class, and choose a Contour Interval (e.g., 10m or 50m). Optionally, set a Base Contour and adjust the Z Factor if needed. Click Run to generate the contours. For better visualization, adjust symbology and enable labeling in the Contents and Labeling panes.

SLOPE ANALYSIS

Slope analysis is a key part of topographic surveys, used to measure terrain steepness for applications like land-use planning, construction, and erosion control. It helps identify stable and unstable areas, guiding decisions on roads, buildings, and drainage. Slope is measured in degrees or percent—higher values mean steeper slopes. To perform slope analysis in ArcGIS Pro, load the DEM, go to Analysis → Tools, and search for the Slope tool under Spatial Analyst Tools → Surface. Set the Input Raster as the DEM, choose an output location, and select the unit (degrees or percent). Apply a Z Factor if needed, then click Run (figure 4.3 shows the slope of the study area). The resulting slope map can be styled with color symbology to show steep and flat areas, supporting better terrain interpretation and planning.

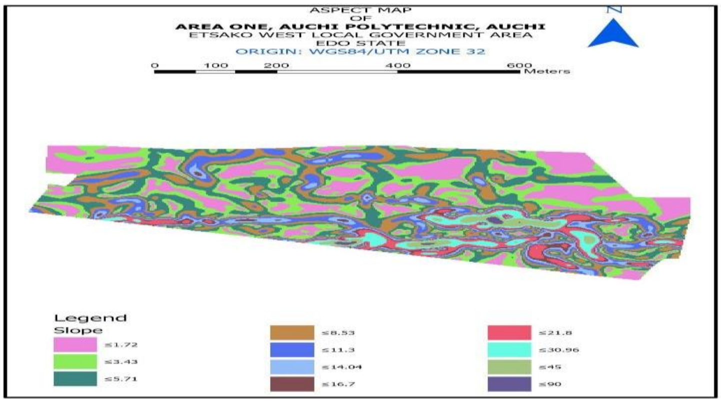


Fig 9: Slope map of the study area.

ASPECT ANALYSIS

Aspect analysis identifies the direction a slope faces, measured in degrees from 0° (north) clockwise to 360°. It's important for understanding sunlight exposure, water runoff, vegetation growth, and planning in fields like agriculture, hydrology, and urban development. For example, south-facing slopes in the Northern Hemisphere get more sunlight, affecting temperature and vegetation. To perform aspect analysis in ArcGIS Pro, add a DEM to your project, then open the Geoprocessing Pane and search for the Aspect tool under Spatial Analyst Tools → Surface. Set the DEM as the input raster, choose an output location for the result, optionally apply a Z factor for elevation adjustment, and click Run (see fig.10). The output raster classifies slope directions, helping with environmental and planning assessments.

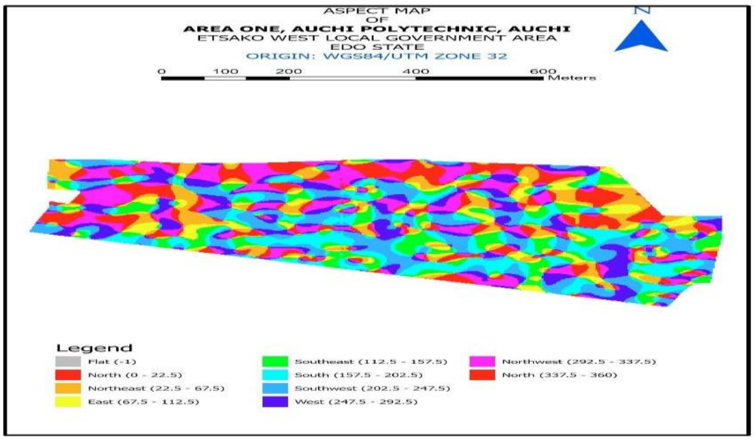


Fig 10: Aspect map of the study area

3D SURFACE ANALYSIS

3D surface analysis in GIS helps visualize terrain by representing elevation data in three dimensions, aiding in understanding landforms, slopes, and visibility. In Surfer, start by preparing your data with X (longitude), Y (latitude), and Z (elevation) values. Open your dataset via File > Open Data, then create a grid using Grid > Data, choosing an interpolation method like Kriging or Inverse Distance

Weighting. After generating the grid, create a 3D surface map through Map > New > 3D Surface Map, selecting your grid file. (fig 11

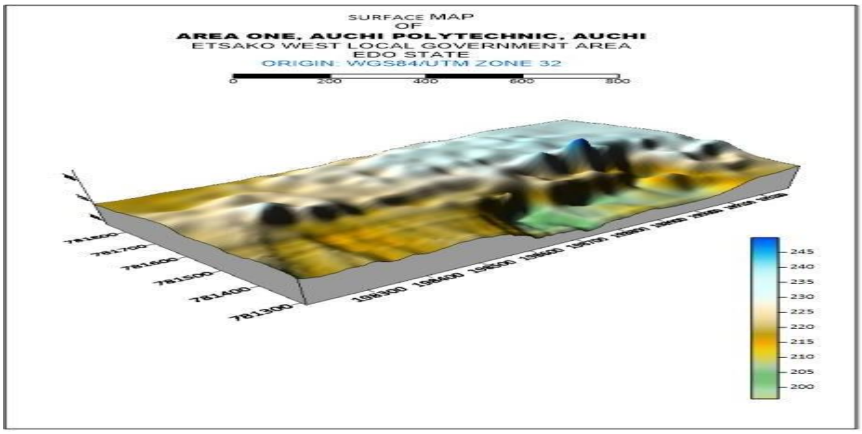


Fig 11: 3D Surface map of the study area

CREATING WIREFRAME OF STUDY AREA

To create a wireframe in Surfer, go to the 3D Surface dropdown menu on the menu bar. Select the Wireframe option and find the Surfer data file created during contour plotting. Click Open, and the software will automatically generate the wireframe of your study area.

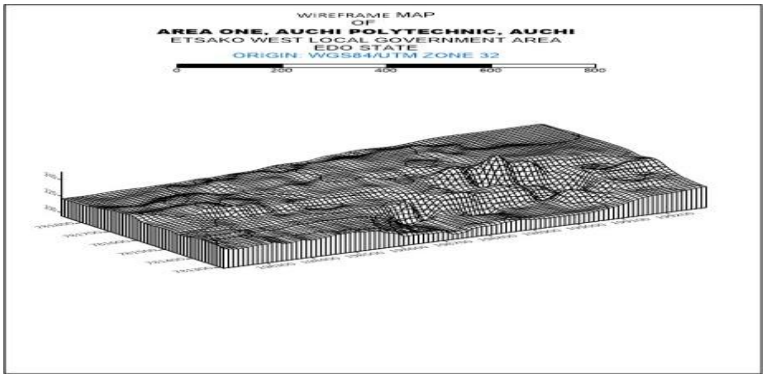


Fig 12: Wireframe map of the study area .

ELEVATION ANALYSIS

Figure 13. shows the elevation map of Auchi Polytechnic, Auchi. The elevation map helps us understand the elevation of the study area at glance. It was reclassified to show low, medium and high elevation. The plan will help the management of the school to know where buildings or project are to be situated in such a way that will facilitate sustainable development within the project area. For instance, buildings constructed on low elevation may be appropriate due to the likelihood of flood.

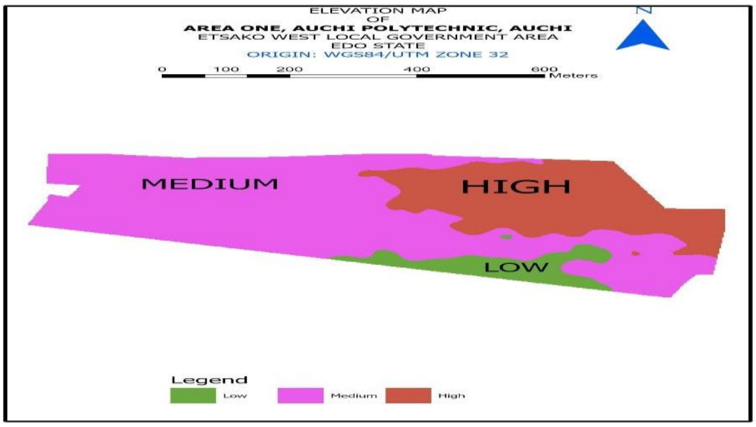


Fig 13: Elevation map of study area

OVERLAY OPERATION

This is the process where two different layers are placed together to generate a new layer showing the relationship that exist between the spatial entities. Fig 14. shows the overlay of buildings on the Triangulated Irregular Network (TIN) map of Auchi Polytechnic, Auchi. The essence of this analysis is to show building that are susceptible to flooding.

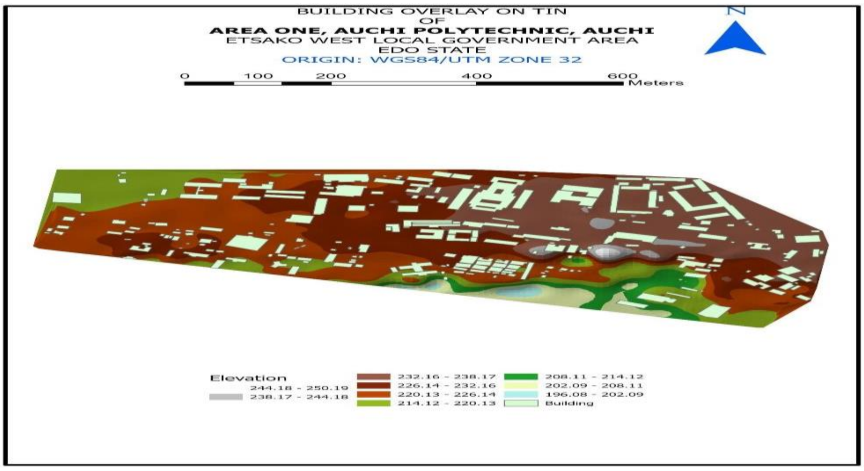


Fig 14: Overlay of Building on TIN map of the study area.

GEOSTATISTICAL ANALYSIS AND QUERYING

Analysis was conducted to determine the percentage of buildings categorized by different elevation ranges, from low to high elevations and also to determine area per each elevation class (Low, Medium and High). The DEM was reclassified into three different classes (Low, Medium and High) using the reclassify tool in ArcGIS Pro

Table 3. Elevation class (Low, Medium and High).

Elevation Class	Area (Hectares)	% w.r.t Total Area
Low	3.022	7.153%
Medium	27.271	64.55%
High	11.954	28.30%
Total	**42.247**	**100%**

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ISSN: 2006- 6775

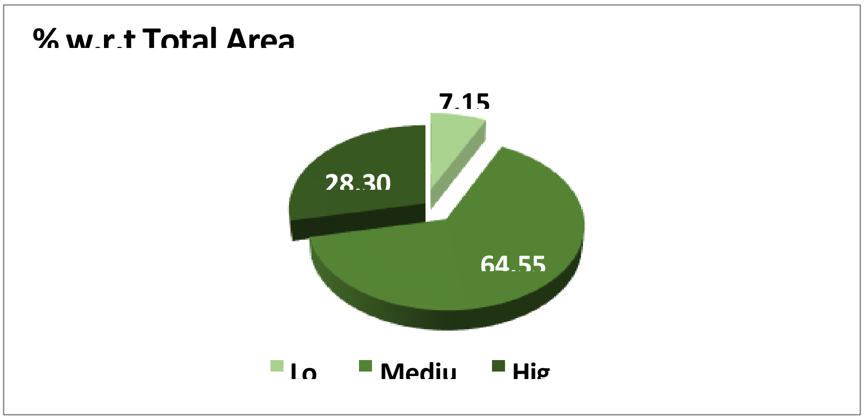

Fig 14: Elevation class (Low, Medium and High).

SINGLE CRITERA QUERY

A single criterion query was carried out using one condition to design the query. The condition retrieved the required information from the database as shown below:

\

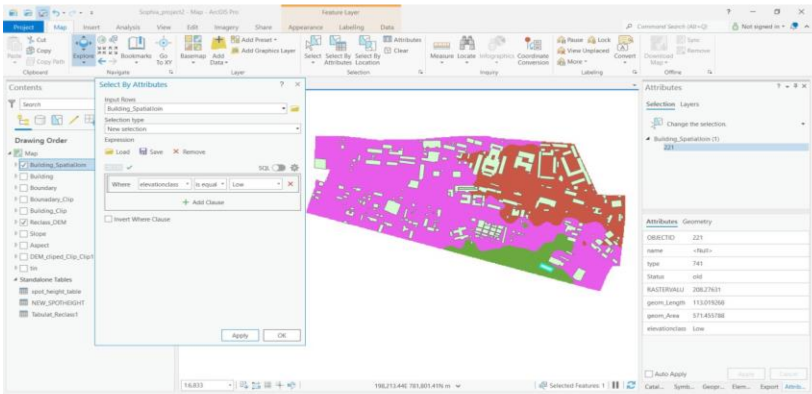

Fig 15a. Querying for buildings on Low Elevation in the study area

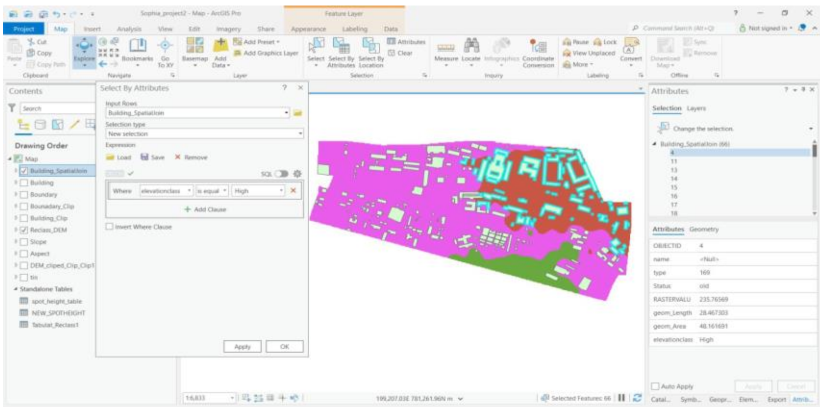

Fig 15b. Query for buildings on High Elevation in the study area.

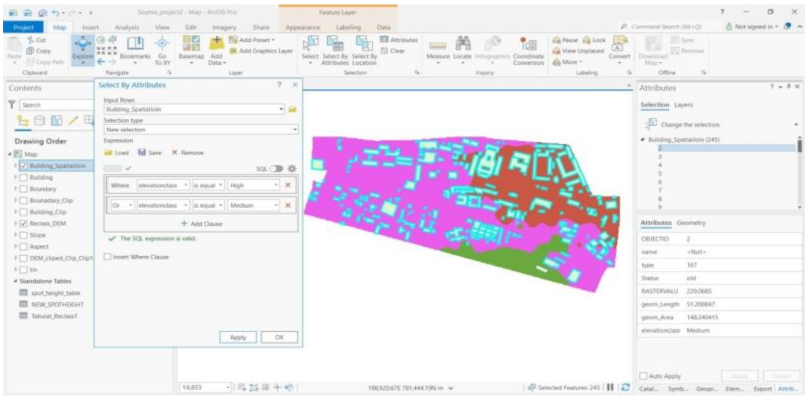

Fig 15c: Query for buildings on medium elevation in the stud yarea.

The next query shows the buildings that are old and new in the study area (fig 16a and 16b)

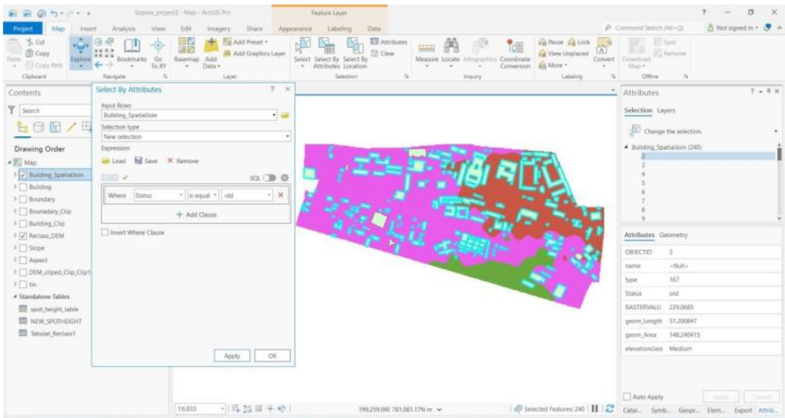

Fig16a. Query for buildings that are old in the study area.
Fig 16 b: Query for buildings that was newly constructed in the study area.

CONCLUSION AND RECOMMENDATION

RECOMMENDATION

Based on the challenges faced and the findings of this project, several recommendations are proposed to improve future topographic mapping and GIS-based studies in Auchi Polytechnic and similar environments. Firstly, it is recommended that the institution invest in modern, high-precision GNSS equipment and ensure regular maintenance and calibration to enhance the accuracy and efficiency of field data collection. There is also a need to improve internet connectivity and data accessibility, as these are critical for downloading high- resolution satellite imagery and accessing cloud-based geospatial tools. Upgrading computing systems with better processing capacity and storage would facilitate faster data analysis and reduce software compatibility issues when working with large datasets in ArcGIS, QGIS, and Surfer. Furthermore, the school management should encourage the regular update of the topographic database, particularly after major infrastructural developments. This ensures that planning decisions are based on current and accurate spatial information. It is also advisable to provide training and capacity-building workshops for staff and students on the use of GIS software and geospatial technologies to promote skill development and project sustainability.

Finally, collaboration between departments and with external geospatial organizations should be encouraged to foster innovation, share technical expertise, and promote the use of topographic information systems for broader planning, research, and environmental management purposes.

CONCLUSION

The development of a Topographic Information System (TIS) for Auchi Polytechnic, Auchi, has successfully demonstrated the importance of integrating mo,dern geospatial technologies such as GNSS and Remote Sensing for accurate and efficient mapping. Through the collection and analysis of both primary and secondary data, this project has produced valuable topographic outputs including Digital Elevation Models (DEMs), Digital Terrain Models (DTMs), slope maps, aspect maps, and hydrologic models. These datasets have been effectively managed using a geospatial database, enabling better decision-making for infrastructure planning, environmental management, and sustainable development.

data-driven planning and encourages the continued

The project has also shown how topographic variations influence building distribution and land use patterns within the institution, providing insights that can guide development and reduce the risk of flooding or poor land allocation. Despite the challenges encountered, the objectives of the project were met, and the resulting TIS provides a comprehensive and up-to-date spatial framework that will serve as a critical tool for academic, administrative, and planning purposes within the Polytechnic. In conclusion, this study highlights the value of digital topographic systems in promoting smarter, infrastructure for long-term institutional growth

use and updating o GIS-based

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TOXICITY AND PHYTOREMEDIATION CAPACI TY OF *Senna Occidentalis* L Subfamily: Caelsapiniodeae GROWN IN HEAVY CONTAMINATED SOIL

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ABSTRACT

Petroleum industries in West Africa particular in Nigeria and the marketing of petroleum products have created problems of oil pollution, a serious environmental concern. Regular spillage of crude oil on the soil reduces the soil's fertility such that most of the essential nutrients are no longer available for plant and crop use. The aim of this study was to determine the toxicity and phytoremediation potentials of plant (*Senna Occidentalis* L.) grown in heavy contaminated soil. The seed of *Senna Occidentalis* (L.) were obtained and planted in a nursery. The soil sample used was collected from the University of Benin, Ekenwan Campus. The spent lubricating oil was obtained from a mechanical workshop in Siluko Road. Five concentrations of spent lubricating oil (0ml, 50ml, 100ml, 150ml, and 200ml) were applied to the soil with *Senna Occidentalis* after transplanting. There was a significant decrease in chlorophyll content level of *Senna Occidentalis* at 100ml, 150ml and 200ml concentrations of spent lubricating and control (0ml) with insignificant decrease observed in chlorophyll content at 50ml concentration and control (0ml). Plant grown on the control soil had higher growth rate within the eight weeks of the experiment while reduced growth rate was observed as the concentration of spent engine oil increased. Fe, Cd, Pb, Cr, Mn, Ag and Zn were significantly accumulated at 200ml concentration (21.17mg/kg, 0.63mg/kg, 2.61mg/kg, 3.61mg/kg, 6.15mg/kg, 0.93mg/kg and 7.10mg/kg). Macronutrient such as Na, K, Ca and Mg significantly reduced with increase in spent lubricating oil concentration (50ml, 100ml, 150ml and 200ml). There was an increase in physiochemical properties of soil polluted with spent lubricating oil compared to control soil samples. This species requires further studies because of its use in phytoremediation of crude oil polluted sites which abound in oil producing countries like Nigeria. The aim of this study was to determine the toxicity and phytoremediation capacity of plant (*Senna Occidentalis*) grown in heavy contaminated soil. The objective of this study is to determine impact of spent lubricating oil on the chlorophyll content index, leaf area, shoot height, leaf number and dry weight of *Senna occidentalis*

Keywords: Pollution, *Senna Occidentalis* (L.), cotaminated soil,). Macronutrient

INTRODUCTION

The petroleum industries in West Africa particularly in Nigeria and the marketing of petroleum products have made oil pollution a serious environmental concern (Okebalama *et al*., 2024; Zhang *et al*., 2022). Also, oil spill from industries, filling stations, loading and pumping stations, petroleum product depots, during transportation and at auto mechanic workshops all added to soil contamination and actually make up a larger percentage of polluted ground in the world versus those contaminated by catastrophic spills (Onwughara *et al*., 2023; Okebalama *et al*., 2024). In Nigeria, oil spills at auto mechanic workshops have been left uncared for over the years and its continuous accumulation is of serious environmental concern, because of the dangers associated with it. For example, the spent motor oil disposed of improperly contains potentially toxic substances such as benzene (carcinogen), lead, arsenic, zinc and cadmium, which can seep into the water tables and contaminate ground water (Adeoye and Omolayo, 2023).

Contamination of soil by petroleum hydrocarbon stimulates indigenous microbial populations, which are capable of utilizing the petroleum hydrocarbons as their carbon and energy source thereby degrading the contaminants. The ability to degrade hydrocarbon substrates is exhibited by a wide variety of bacteria genera (Eze *et al*., 2021; Alfelor *et al*., 2023). Using culture dependent and independent isolation techniques different bacterial genera have been characterized from hydrocarbon polluted soils in different geographical and ecological contexts (Adeoye and Omolayo, 2023; Oladipo *et al*., 2021).

Phytoremediation

Phytoremediation process is a plant-based approach, which involves the use of plants to extract and remove elemental pollutants or lower their bioavailability in soil (Ibrahim *et al*., 2022; Zhang *et al*., 2021). Plants have the abilities to absorb ionic compounds in the soil even at low concentrations through their root system. Plants extend their root system into the soil matrix and establish rhizosphere ecosystem to accumulate heavy metals and modulate their bioavailability, thereby reclaiming the polluted soil and stabilizing soil fertility (Nwankwo *et al*., 2019; Eze *et al*., 2021). There are advantages of using phytoremediation, which include: (i) economically feasible phytoremediation is an autotrophic system powered by solar energy, therefore, simple to manage, and the cost of installation and maintenance is low, (ii) environment and eco-friendly—it can reduce exposure of the pollutants to the environment and ecosystem, (iii) applicability—it can be applied over a large-scale field and can easily be disposed, (iv) it prevents erosion and metal leaching through stabilizing heavy metals, reducing the risk of spreading of contaminants, (v) it can also improve soil fertility by releasing various organic matters to the soil (Ibrahim *et al*., 2022; Adeoye and Omolayo, 2023; Zhang *et al*., 2022). During the past decades, numerous studies have been conducted to understand the molecular mechanisms underlying heavy metal tolerance and to develop techniques to improve phytoremediation efficiency. In the current review, the mechanisms of how heavy metals are taken up and translocated in plants are described, and the detoxification strategies (avoidance and tolerance) adopted by plants in response to heavy metal have been discussed.

Large scale pollutions of both the terrestrial and aquatic environment in oil polluted soil due to activities of the oil industries has been documented (Zhang *et al*., 2021; Adeoye and Omolayo, 2023). Bioremediation has long been applied as a treatment technology that is cost-effective, ecologically friendly and efficient for the decontamination of hydrocarbon polluted soils (Eze *et al*., 2021). Bioremediation techniques for removing petroleum hydrocarbons in the soil are developed around strategies for delivering moisture, aeration and nutrients in order to optimize microbial activity and degradation of the pollutants (Eze *et al*., 2021; Alfelor *et al*., 2023).

EFFECT OF CRUDE-OIL POLLUTION ON PLANT GROWTH

Plants need water, air and nutrient for them to germinate and grow. Frequent spillage of crude oil on the soil makes the soil toxic and unproductive. The oil reduces the soil's fertility such that most of the essential nutrients are no longer available for plant and crop utilization. Zhang *et al*. (2022) reported that spilled crude-oil, reduces and restricts permeability these are organic hydrocarbons which fill the soil pores expel water and air, thus depriving the plant roots the much needed water and air. Soil properties involved in soil-plant-water relationship are degradable and include texture, infiltration, hydraulic conductivity, moisture content, pH and density, which affect root and leaf development and plant growth and yield (Alabi *et al*., 2020; Ibrahim *et al*., 2022). Adewumi *et al*. (2021) demonstrated the effect of pollution on germination, growth and nutrient uptake using pawpaw. Ogunjobi *et al*. (2021) reported that crude-oil spillage has frequented the alluvial soils of the coastal plains of the Qua Iboe river wetlands in Akwa Ibom State, Nigeria and deprived the communities of their socioeconomic livelihood. This, in turn, has fostered hostility towards the oil companies when neither the government nor the oil companies acted quickly to accommodate or alleviate effect of the degradation (Okebalama *et al*., 2024; Adeoye and Omolayo, 2023).

Therefore, remediation should be done to resolve ecological humiliation that has formed economic suffering on their agricultural living. Bioremediation and natural rehabilitation, however, take prolonged period and can isolate the actual people affected by the problem from the solution (Ibrahim *et al*., 2022). Therefore, an approach that better involves the affected people in a quick solution could be the chemical remediation whereby they could watch, or even participate, as the restoration process is expected to take a short period (Adeoye and Omolayo, 2023).

SENNA OCCIDENTALIS

Senna Occidentalis is an erect hairless under shrub, annual or sometimes biennial. It grows to about 120cm high and reproduces from seeds. The stem is ribbed, wooden below and with loosely branching. The leaves are compound, pinnate, alternate and 12 – 18 cm long. The leaflets are 4 – 6 pairs, broadly lanceolate, 3 – 8 cm long and 1 – 2 cm wide. The upper pair of leaflets is always larger. The inflorescence is axillary raceme with yellow flowers. Fruit is flat, slightly curved and green in colour (Ogunjobi *et al*., 2021; Adewumi *et al*., 2021). The pods are smooth, 16 cm long and 7 mm wide, with 20 – 30 brown ovate seeds that are about 4mm across. The common name is coffee senna, and it is a common weed in feed crops, waste areas and road sides in West Africa (Adeoye and Omolayo, 2023; Okebalama *et al*., 2024).

.Materials

The seeds of *Senna Occidentalis* were obtained and planted in a nursery. The seeds were obtained and then used for the research. The soil sample used was collected from the University of Benin, Ekenwan Campus. The spent lubricating oil was obtained from a mechanical workshop in Okada Town. A graduated cylinder was used to measure the volume of spent lubricating oil (SLO) used for the experiment. The graduated cylinder was collected from the laboratory in the Department of Science Laboratory and Technology. The weighing balance used to weigh the soil samples was also collected from the laboratory. Plastic bowls used for planting the seedlings were obtained from the Oba market in Benin City.

Experimental Method

The experimental set-up was arranged on a cleared pieces of land situated within the premises of the University of Benin, Ekenwan Campus. Loamy soil used for the experiment was properly mixed, put into 25 by 15cm perforated bowls to a weight of 5 kg using a weighing balance. Spent lubricating oil of difference volumes (50 ml, 100 ml, 150 ml route,

and 200 ml) was carefully introduced into each of the weighed pot of soil. The set-up was left for six weeks for natural attenuation to occur before transplanting form the nursery.

Plant Growth Measurement

The height of each plant was measured at regular interval of seven days from the soil to the terminal bud using a simple meter rule. The leaves produced were counted every 7 days (Odjegba and Sadig, 2002). The leaf area was determined by the proportional method of weighing a cut out of traced area with a standard paper of known weight to area ratio. An electric balance was used for weighing.

Total leaf area per plant was calculated by proportion as:

Standard paper weight = Y
Standard paper area = X
Specimen/trace paper weight = Y_1
Specimen/trace paper area = X_1

By ratio, $\frac{\text{Standard paper weight}}{\text{Standard paper area}} = \frac{\text{Specimen paper weight}}{\text{Specimen traced paper area}}$

Specimen/trace paper area = $\frac{\text{Specimen/trace paper weight x Standard paper area}}{\text{Standard paper weight}}$

$Y/X = Y_1/X_1$

X1 = (Y1, X)/Y ……

Lead area (for specimen) = specimen weight x standard area/standard area weight

Percentage Inhibition (%)

The percentage inhibition of *Senna Occidentalis* at different concentration was determined at the end of the experiment using the formula below; $\% \, \text{Inhibition} = \frac{C-Xi}{C} x \frac{100}{1}$

C = growth gradient in treatment

Xi = growth in experiment

Bioconcentration Factor

Bioconcentration is described as a measure of amount of chemical residue in an organism's tissue relative to the concentration in the organism's environment Bioconcentration factor (BCF) = Concentration in biota/concentration in the environment.

Leaf Chlorophyll Content

Chlorophyll content of the leaves was measured using the Apogee chlorophyll content metre CCM-200 plus. Measurement was done by holding down the arm of the sample head on the intact leaf until a beef was heard. The chlorophyll content was displayed on the screen of the device.

Fresh Weight and Dry Weight

Samples of the leaf, stem and root were collected from each treatment to determine the fresh weight and dry weight after 8 weeks of treatment following the method of Hunt (1990). At harvest, the root system was retrieved by immersing in water and washing carefully. Fresh weight was determined in the laboratory using electrical weighing balance. The samples were later dried in an oven at $60^{o}C$ for 72 hours to determine their dry weights. Four replicates were used for each treatment.

RESULTS

Table 1 shows the effect of spent lubricating oil (SLO) on the chlorophyll content index of *Senna Occidentalis*. There was a significant decrease in chlorophyll content level of *Senna Occidentalis* at 0ml (0%), 100ml (2%), 150ml (3%) and 200 ml (4%) concentrations of spent lubricating and control (ml) while no significant decrease was observed in chlorophyll content at 50% concentration and control (ml). The highest chlorophyll content was recorded in control (14.42±0.07) while the lowest chlorophyll content was recorded in 4% SLO concentration treatment (3.23±0.32)

The results for the effect of spent lubricating oil (SLO) on the leaf area of *Senna Occidentalis*is presented in Table 2. There was a significant decrease in leaf area of *Senna Occidentalis* as spent lubricating oil concentration increased from 50ml, 100ml, 150ml and 200ml compared to control samples (0%). The highest leaf area was recorded in control samples (28.31 ± 2.01cm^2) while the smallest leaf area was recorded in 4% SLO concentration treatment (7.48 ± 0.97cm^2).

The effect of spent lubricating oil on shoot height of *Senna Occidentalis*is is presented in Table 3. There was a significant reduction in shoot height with increase in concentration of spent lubricating oil treatments. There was a significant decrease in shoot height of *Senna Occidentalis* from 17.61±0.49cm to 4.10±0.19cm, 18.15±1.06cm to 6.07±0.55cm, 18.99±1.11cm to 7.97±0.41cm, 19.08±1.04cm to 9.05±0.24cm, 19.77±.1.24cm to 9.19±0.49cm, 21.20±1.65cm to 9.88±0.79cm, 21.66±1.88cm to 10.08±1.05cm and 22.33±0.57cm to 10.24±0.68cm treated with 50ml, 100ml, 150ml and 200ml concentrations of spent lubricating oil at week 1, 2, 3, 4, 5, 6, 7 and 8 respectively compared to control treatment (0%) ($p<0.05$).

Table 1: Effect of spent lubricating oil (SLO) on the chlorophyll content index of *Senna* ***Occidentalis***

Concentration of SLO	**(ml)**	**Chlorophyll content index**
0	0	14.42±0.07
1	50	11.30±0.17
2	100	8.32±0.61
3	150	5.14±0.01
4	200	3.23±0.32

Values are means and standard error of 4 replicates P>0.05

Table 2: Effect of spent lubricating oil (SLO) on the leaf area of *Senna Occidentalis*

Concentration of SLO (%)	**(ml)**	Leaf area (cm^2)
0	0	28.31 ± 2.01
1	50	21.81± 1.80
2	100	17.10±2.03
4	200	7.48 ± 0.97

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Values are means and standard error of 4 replicates P>0.05

Table 3: Effect of spent lubricating oil (SLO) on shoot height (cm) of *Senna Occidentalis*

Concentration of SLO (%)	Average shoot height (cm) WK1	WK2	WK3	WK4	WK5	WK6	WK7	WK8
0	17.61±0.49	18.15±1.06	18.99±1.11	19.08±1.04	19.77±.1.24	21.20±1.65	21.66±1.88	22.33±0.57
1	12.49±0.28	15.30±0.96	15.79±1.06	16.35±1.51	17.88±0.68	19.70±1.14	19.99±1.67	20.55±1.33
2	10.18±0.23	13.22±0.84	14.24±1.78	14.95±1.01	15.15±0.72	15.27±0.68	16.97±0.76	18.34±0.51
3	7.41±0.66	10.87±0.76	11.38±0.99	11.89±0.96	12.45±0.29	12.79±2.55	13.06±0.45	13.41±0.19
4	4.10±0.19	6.07±0.55	7.97±0.41	9.05±0.24	9.19±0.49	9.88±0.79	10.08±1.05	10.24±0.68

Values are means of four replicate ± S.E

P>0.05

Table 4: Effect of spent lubricating oil (SLO) on leaf number of *Senna Occidentalis*

Concentration of SLO (%)	Weeks after application WK1	WK2	WK3	WK4	WK5	WK6	WK7	WK8
0	10.86±0.04	10.88±0.55	11.22±0.54	11.87±1.24	13.39±0.12	15.05±.0.18	18.57±4.44	21.31±1.75
1	8.53±0.24	8.55±0.10	9.75±0.94	9.66±1.26	10.29±1.64	10.95±0.03	12.31±2.66	17.74±2.00
2	7.27±0.19	7.94±0.65	8.45±1.55	8.88±1.94	9.33±0.69	10.04±0.64	11.01±3.01	11.21±1.46
3	6.38±0.14	7.52±0.22	7.83±0.37	8.13±0.66	8.59±1.01	8.51±0.60	9.62±2.16	10.38±1.40
4	4.20±0.29	5.20±0.01	5.16±0.09	6.27±0.75	6.97±0.02	7.05±0.24	7.99±2.79	8.01±0.35

Values are means of four replicate ± S.E
P>0.05

Table 4 shows the effect of spent lubricating oil (SLO) on leaf number of *Senna Occidentalis*. There was a significant decrease in the leaf number of *Senna Occidentalis* as the concentration of spent lubricating oil increased (50ml, 10ml, 150ml and 200ml) (P<0.05). However, increase in leaf number was observed as the week of application increased. Leaf number reduced from 10.86±0.04 to 4.20±0.29, 10.88±0.55 to 5.20±0.01, 11.22±0.54 to 5.16±0.09, 11.87±1.24 to 6.27±0.75, 13.39±0.12 to 6.97±0.02, 15.05±0.18 to 7.05±0.24, 18.57±4.44 to 7.99±2.79 and 21.31±1.75 to 8.01±0.35 at 50ml, 10ml, 150ml and 200ml spent lubricating oil concentration treatment from week 1 to week 8 respectively.

The effect of spent lubricating oil on the physicochemical properties of soil sown with *Senna Occidentalis*is presented in Table 5. There was an increase in pH content from 5.17 to 8.14 of the soil sample with increase in spent lubricating oil concentration compared to control (5.23). This indicates the soil was slightly acidic before being polluted with spent lubricating oil. The addition of spent lubricating oil made the soil less acidic and more alkaline. Phosphate level was observed to increase mg/kg (5%) compared to control samples (0.21 mg/kg)

with increase in concentration of spent lubricating oil in the soil from 0.92mg/kg (0%) to 2.83mg/kg (5%).

There was also increase in Sulphate level with increase in concentration of spent lubricating oil from 1.90 to 6.10mg/kg compared to control samples (1.84 mg/kg). Ammonium increase with increase in concentration of spent lubricating oil from 1.00mg/kg (1%) to 3.14mg/kg (4%) compared to control samples (0.96mg/kg). There was a significant increase in Iron content with increase in concentration of spent lubricating oil from 3.84 mg/kg (1%) to 5.69 mg/kg (4%) compared to control samples (1.11 mg/kg). There was also an increase in level of cadmium with increase in concentration of spent lubricating oil from 0.09mg/kg (1%) to 0.23 mg/kg (5%) compared to control samples (0.04 mg/kg). Lead level increased with increase in concentration of spent lubricating oil from 0.31 mg/kg (1%) to 0.62 mg/kg (4%) compared to control samples (0.24 mg/kg).

There was an increase in chromium level with increase in concentration of spent lubricating oil from 0.32 mg/kg (1%) to 1.28

Manganese increased from 0.40mg/kg (1%) to 0.63mg/kg (4%) with increase in concentration of spent lubricating oil compared to control samples (0.31%). There was a significant increase in arsenic content with increase in concentration of spent lubricating oil from 0.30 mg/kg (1%) to 0.57 mg/kg (5%) compared to control samples (0.25 mg/kg). Sodium content increased from 1.16 mg/kg (1%) to 2.14 mg/kg (4%) with increase in concentration of spent lubricating oil compared to control samples (0.99%). Potassium content decreased from 1.84 mg/kg (1%) to 0.88 mg/kg (4%) with increase in concentration of spent lubricating oil compared to control samples (2.46 %). Level of calcium increased from 0.86 mg/kg (1%) to 1.37 mg/kg (4%) with increase in concentration of spent lubricating oil compared to control samples (0.61%). Magnesium content increased from 0.63 mg/kg (1%) to 1.04 mg/kg (4%) with increase in concentration of spent lubricating oil compared to control samples (0.55 %). There was an increase in total nitrogen and organic carbon contents of the polluted soil compared to control soil samples. This increase may be due to application of spent lubricating oil to the soil. Organic matter content increased from 1.06 to 2.02 with increase in volume of spent lubricating oil compared to control samples (0.42). Total hydrocarbon content increased from 73.03mg/kg (1%) to 203.02mg/kg (4%) with increase in spent lubricating oil when compared to control (64.49mg/kg)

Table 5: Effect of spent lubricating oil on the physicochemical properties of soil sown with *Senna Occidentalis*

Concentration of oil (%)	pH	PO_4	SO_4	NH_4	Fe	Cd	Pb	Cr	Mn	As	Na	K	Ca	Mg	T.N	O.C	O.M	THC
0	5.21	0.90	1.80	0.95	1.10	0.03	0.23	0.22	0.30	0.24	0.95	2.44	0.62	0.54	0.15	0.40	0.96	64.51
1	5.17	1.10	1.90	1.01	3.85	0.10	0.31	0.32	0.40	0.30	1.18	1.84	0.86	0.63	0.27	0.42	1.06	73.03
2	7.42	2.01	2.31	2.00	4.15	0.10	0.39	0.43	0.53	0.38	1.24	1.45	1.06	0.76	0.37	0.55	1.24	125.06
3	7.89	2.15	4.01	2.25	5.25	0.21	0.40	0.60	0.52	0.45	1.87	1.87	1.28	0.90	0.42	0.57	1.35	193.22
4	8.14	2.80	6.10	3.15	5.71	0.24	0.62	1.28	0.63	0.57	2.15	0.88	1.37	1.04	0.52	1.04	2.02	203.02

Key:
E.C = Electrical conductivity, T.N = Total nitrogen, T.O.C = Total organic carbon, T.H.C = Total hydrocarbon content
P = phosphorus, K = potassium Mg = magnesium, Na= sodium, Ca = calcium, Fe = Iron,
Cr = Chromium, Pb = Lead, Cu = copper

DISCUSSION

Spent lubricant oil affected the growth indices of *Senna Occidentalis*the plant negatively shown by reduced plant height, number of leaves, weight of plant and leaf area. Researchers like Amadi *et al*. (2018) recorded a growth rate reduction of *Senna Occidentalis* L. by as much as 80% caused by the effect of petroleum hydrocarbons. Similarly, Alabi *et al*. (2020) reported a reduction in plant weight as is seen here in this study. On the other hand Adewumi *et al*. (2021) working on weeds like *Centrosema brasillianum* and *P. maximum* also recorded reduced plant growth. This study also recorded reduced plant height which agrees with the work of Ogunjobi *et al*. (2021).

The authors recorded similar results caused by petroleum hydrocarbons in diesel fuel and inferred that the negative effect could be due to the impermeability effect of petroleum hydrocarbons or immobilization of nutrients mainly nitrogen or inhibitory effect of some polycyclic aromatic compounds. Ibrahim *et al*., (2022) reported the bioremediation of crude oil polluted soil using *Vernonia amagdylina* and manure. Zhang *et al*. (2022) observed poor germination of *Capsicum annum* and *Lycopersicon esculentum*. Oladipo *et al*. (2021) observed the effect of crude oil contaminated soil on biomass accumulation in *Jatropha curcas L* seedlings. Eze *et al*. (2021) reported the effect of spent engine oil as a soil contaminant on the growth of two egg plant species, *Selenium belonging* L. and *S. inanes* L.

The tolerance of *Chromolaena odorata* (L) K. and R. grown in soil contaminated with spent lubricating oil was also reported by Zhang *et al*. (2022). Nwankwo *et al*. (2019) on the other hand says the effect is a plant sensitive response to chemical substances. Research also show that the plant that are able to grow in contaminated sites take up long chain (heavy) alkanes into their roots rapidly and slowly translocate them stems and leaves as result of their low solubility in water (Ibrahim *et al*., 2022; Adeoye and Omolayo, 2023). Other explanations proffered for this reduced growth is the effect of small aliphatic, aromatic, naphthalic and phenolic like compounds in crude oil that may reduce respiration, transpiration and photosynthesis II and hormonal stress response (Nwankwo *et al*., 2019; Eze *et al*., 2021).

These effects however vary with individual plant species and their physiological responses to contaminants (Ogunlebiyi *et al*., 2020). Phytotoxicity assays help in selecting plant species that are able to withstand high levels of contaminants and screening out those that are not able to establish themselves in such conditions as present in contaminated sites (Adeoye and Omolayo, 2023). The continued growth of the plant in the presence of the contaminant and other growth indices particularly biomass can determine if the plant is a potential phytoremediant. In this study, *Senna Occidentalis* was able to withstand high levels of oil contamination and the dry weight records show that there was no significant difference between the plants that received high doses of the contaminant and the control that had no contaminant.

The plant is therefore a good candidate for remediation of crude oil contaminated sites. This agrees with Alabi *et al*. (2020) which selected *Senna Occidentalis* and *Cyndon dactylon* as the best candidate for petroleum contaminated sites on the basis its high resistance to phytotoxic compounds in petroleum contaminated sites. The concentrations used in this study affected its performance. Higher plant density improved performance of the plant against contaminant stress. Dry weights were higher at concentration of 5.0 %(v/w). This study also agrees with that of Adewumi *et al*. (2021) which concluded that higher plant density improves performance of the plant against environmental stress of contamination. The study also agrees with that of Ogunjobi *et al*. (2021) which concluded that higher standing crop density improved the performance of plant like *Paspalum vaginatum* in the remediation of dredge soil in the Niger Delta of Nigeria.

Conclusion

The result indicated that *Senna Occidentalis* can be used for phytoremdiation due to its tolerance to heavy metals present in spent lubricating. Though, the plant growth was affected by high concentrations of spent lubricating oil. This specie requires further study with respect to its use in phytoremediation of crude oil polluted sites.

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TOXICITY AND PHYTOREMEDIATION POTENTIALS OF *Indigofera tinctoria* L. (true indigo) Subfamily: Palpilionoideae PLANTED IN HEAVY METAL CONTAMINATED SOIL

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ABSTRACT

The petroleum industries in West Africa, particularly in Nigeria and the marketing of petroleum products have made oil pollution a serious environmental concern. Frequent spillage of crude oil on the soil reduces the soil's fertility such that most of the essential nutrients are no longer available for plant and crop utilization. The aim of this study was to determine the toxicity and phytoremediation potentials of (*Indigofera tinctoria* L.) planted in heavy metal contaminated soil. The seed of *Indigofera tinctoria* (L.) were obtained and planted in a nursery. The soil sample used was collected from Iguogie community in Ovia North East Local Government Area in Edo State. The spent lubricating oil was obtained from a mechanical workshop in Erhumwunse Street, City. Five concentrations of spent lubricating oil (0ml, 50ml, 100ml, 150ml and 200ml) were applied to the soil with *Indigofera tinctoria* L. after transplanting. There was a significant decrease in chlorophyll content level of *Indigofera tinctoria* L. at 0ml, 50ml, 100ml, 150ml and 200ml concentrations of spent lubricating and control (0ml) while no significant decrease was observed in chlorophyll content at 50ml concentration and control (0ml). Plant grown on the control soil had higher growth rate throughout the eight weeks of the experiment while reduced growth rate was observed as the concentration of spent engine oil increased. Fe, Cd, Pb, Cr, Mn, Ag and Zn were significantly accumulated at 5% concentration (21.18mg/kg, 0.65mg/kg, 2.62mg/kg, 3.61mg/kg, 6.17mg/kg, 0.96mg/kg and 7.12mg/kg). Macronutrient such as Na, K, Ca and Mg significantly reduced with increase in spent lubricating oil concentration (0ml, 50ml, 100ml, 150ml and 200ml). There was an increase in physiochemical properties of soil polluted with spent lubricating oil compared to control soil samples. This species deserve further study because of its use in phytoremediation of crude oil polluted sites which abound in oil producing countries like Nigeria.

INTRODUCTION

The petroleum industries in West Africa, particularly in Nigeria and the marketing of petroleum products have made oil pollution a serious environmental concern. Also, oil spill from industries, filling stations, loading and pumping stations, petroleum product depots, during transportation and at auto mechanic workshops all contribute to soil contamination, and actually make up a larger percentage of polluted ground in the world versus those contaminated by catastrophic spills (Okebalama *et al*., 2024; Ogundele and Okoro, 2022). In Nigeria, oil spills at auto mechanic workshops have been left uncared for over the years and its continuous accumulation is of serious environmental concern, because of the hazard associated with it (Okebalama *et al*., 2024). For instance, the spent motor oil disposed off improperly contains potentially toxic substances such as benzene (carcinogen), lead, arsenic, zinc and cadmium, which can seep into the water tables and contaminate ground water (Onwughara *et al*., 2023).

Petroleum hydrocarbon stimulates indigenous microbial populations, which are capable of utilizing the petroleum hydrocarbons as their carbon and energy source thereby degrading the contaminants. The ability to degrade hydrocarbon substrates is exhibited by a wide variety of bacteria genera (Alfelor *et al*., 2023; Eze *et al*., 2021). Using culture dependent and independent isolation techniques different bacterial genera have been characterized from hydrocarbon polluted soils in different geographical and ecological contexts (Adeoye and Omolayo, 2023; Oladipo *et al*., 2021).

Phytoremediation

Phytoremediation is a plant-based approach, which involves the use of plants to extract and remove elemental pollutants or lower their bioavailability in soil (Ibrahim *et al*., 2022). Plants have the abilities to absorb ionic compounds in the soil even at low concentrations through their root system. Plants extend their root system into the soil matrix and establish rhizosphere ecosystem to accumulate heavy metals and modulate their bioavailability, thereby reclaiming the polluted soil and stabilizing soil fertility (Jacob *et al*., 2018; DalCorso *et al*., 2019). There are advantages of using phytoremediation, which include: (i) economically feasible—phytoremediation is an autotrophic system powered by solar energy, therefore, simple to manage, and the cost of installation and maintenance is low, (ii) environment and eco-friendly—it can reduce exposure of the pollutants to the environment and ecosystem, (iii) applicability—it can be applied over a large-scale field and can easily be disposed, (iv) it prevents erosion and metal leaching through stabilizing heavy metals, reducing the risk of spreading of contaminants, (v) it can also improve soil fertility by releasing various organic matters to the soil (Zhang *et al*., 2021; Nwankwo *et al*., 2019; Jacob *et al*., 2018). During the past decades, numerous studies have been conducted to understand the molecular mechanisms underlying heavy metal tolerance and to develop techniques to improve phytoremediation efficiency. In the current review, the mechanisms of how heavy metals are taken up and translocated in plants are described, and the detoxification strategies (avoidance and tolerance) adopted by plants in response to heavy metal have been discussed (Eze *et al*., 2021; Alfelor *et al*., 2023).

Large scale pollutions of both the terrestrial and aquatic environment in oil polluted soil due to activities of the oil industries has been documented (Zhang *et al*., 2021; Adeoye and Omolayo, 2023; Ibrahim *et al*., 2022).. Bioremediation has long been applied as a treatment technology that is cost-effective, ecologically friendly and efficient for the decontamination of hydrocarbon polluted soils (Nwankwo *et al*., 2019; Eze *et al*., 2021). Bioremediation techniques for removing petroleum hydrocarbons in the soil are developed around strategies for delivering moisture, aeration and nutrients in order to optimize microbial activity and degradation of the pollutants (Ogunlebiyi *et al*., 2020; Adeoye and Omolayo, 2023). The aim of this study was to determine the toxicity and phytoremediation potentials of (*Indigofera tinctoria* L.) planted in heavy metal contaminated soil. The seed of *Indigofera tinctoria* (L.) were obtained and planted in a nursery. The objective of were to determine the impact of spent lubricating oil on the chlorophyll content index, leaf area, shoot height, leaf number and dry weight of *Indigofera tinctoria* (L.)

***Indigofera tinctoria* (L.)**

It is an erect, annual to short leave perennial herb from 50 to 110 cm tall, much branched. It has stem that are terete, reddish-green to brown and covered with white. The leaves are spirally arranged, shortly petiolate, staples triangular, imparipinately compound, 12 to 15 leaflets, blade – elliptical to obovate, 2-3 1 x 1.5mm, base obtuse to rounded, rearly oblique, adaxial usually glabrous, abaxial surface, finely hairy, faintly veined, margins entire, Apex rounded to obtuse (Adeoye and Omolayo, 2023). The florescence are auxiliary racemes, up to 7cm long, subtended by triangular bracts, sessile, man flowered. Flowers are bisexual, zygomophy, lobes, triangular up to 4mm in diameter. 5-merous whitish with reddish to pinkish rays, covered with oppressed white hairs (Oladipo *et al*., 2021).. The fruits are cylindrical pores, linear 20-35 x 2-3mm, pointed at both ends, slightly recurved or straight, green to redish-brown, faint constriction, 8-10 seeded. The seeds are oblong or subglobose, rhomboid towards one end, 1 – 1.5 x 1.5 – 2mm. it occurs on rocky bank in the savannah. The foliage is an excellent folder for livestocks (Ogundele and Okoro, 2022)..

Materials

The seeds of *Indigofera tinctoria* were obtained and planted in a nursery. The seeds were obtained and then used for the research. The soil sample used was collected from the Edo State Polytechnic, Usen Botanical Garden. The spent lubricating oil was obtained from a mechanical workshop in Iguobazuwa Town. A graduated cylinder was used to measure the volume of spent lubricating oil (SLO) used for the experiment. The graduated cylinder was collected from the laboratory in the Department of Science Laboratory and Technology. The weighing balance used to weigh the soil samples was also collected from the laboratory. Plastic bowls used for planting the seedlings were obtained from the Iguobazuwa market in Ovia Southwest Local Government Area, Benin City.

The experimental set-up was arranged on a cleared pieces of land situated within the premises of the Edo State Polytechnic Usen. Loamy soil used for the experiment was properly mixed, put into 25 by 15cm perforated bowls to a weight of 5 kg using a weighing balance. Spent lubricating oil of difference volumes (50 ml, 100 ml, 150 ml and 200 ml) was carefully introduced into each of the weighed pot of soil. The set-up was left for six weeks for natural attenuation to occur before transplanting form the nursery.

Plant Growth Measurement

Bioconcentration Factor

Bioconcentration is described as a measure of amount of chemical residue in an organism's tissue relative to the concentration in the organism's environment

Bioconcentration factor (BCF) = Concentration in biota/concentration in the environment.

Leaf Chlorophyll Content

areas, grassy fields, arable farm lands, road sides, woodland margins, riparian and on river

The height of each plant was measured at regular interval of seven days from the soil to the terminal bud using a simple meter rule. The leaves produced were counted every 7 days (Odjegba and Sadig, 2002). The leaf area was determined by the proportional method of weighing a cut out of traced area with a standard paper of known weight to area ratio. An electric balance was used for weighing.

Total leaf area per plant was calculated by proportion as:

Standard paper weight = Y

Standard paper area = X

Specimen/trace paper weight = Y_1

Specimen/trace paper area = X_1

By ratio, Standard paper weight = Specimen paper weight

Standard paper area

Specimen traced paper area

Specimen/trace paper area = Specimen/trace paper weight x Standard paper area

Standard paper weight

$Y/X = Y_1/X_1$

X1 = (Y1, X)/Y ……

Lead area (for specimen) = specimen weight x standard area/standard area weight

Percentage Inhibition (%)

The percentage inhibition of *Indigofera tinctoria* at different concentration was determined at the end of the experiment using the formula below;

$$\% \text{ Inhibition} = \frac{C - Xi}{C} x \frac{100}{1}$$

C = growth gradient in treatment

Xi = growth in experiment

Chlorophyll content of the leaves was measured using the Apogee chlorophyll content metre CCM-200 plus. Measurement was done by holding down the arm of the sample head on the intact leaf until a beef was heard. The chlorophyll content was displayed on the screen of the device.

Fresh Weight and Dry Weight

Samples of the leaf, stem and root were collected from each treatment to determine the fresh weight and dry weight after 8 weeks of treatment following the method of Hunt (1990). At harvest, the root system was retrieved by immersing in water and washing carefully. Fresh weight was determined in the laboratory using electrical weighing balance. The samples were later dried in an oven at 60^{o}C for 72 hours to determine their dry weights. Four replicates were used for each treatment.

Determination of heavy metals in seeds of *Indigofera tinctoria*

The leaves of *Indigofera tinctoria* samples were digested using a tri-acid mixture consisting of 65% sulphuric acid (H_2SO_4), 65% perchloric acid ($HClO_4$), and 70% nitric acid (HNO_3) in the ratio of 1:1:5. One gram of the dried powdered sample was placed in a 100 cm³ beaker and treated with 15 cm³ of the tri-acid solution. The mixture was heated at 80 °C until a clear solution was obtained for heavy metal determination. After digestion, the solution was allowed to cool and was then filtered. The filtrate was diluted to a final volume of 50 cm³ using distilled water. Concentrations of heavy metals (Zn, Cu, Mn, Cr, Ni, Pb, Fe, and Cd) were determined using an Atomic Absorption Spectrophotometer (Solar 969 Unicam series).

Determination of physicochemical properties of soil samples

Determination of Soil pH

Soil pH was determined using a digital pH meter. A soil–water suspension was prepared in the ratio of 1:2.5 (w/v). The mixture was stirred and allowed to stand for 30 minutes. The pH meter was calibrated using standard buffer solutions, after which the electrode was immersed in the suspension and readings were recorded.

Determination of Exchangeable Sodium, Potassium, Calcium, and Magnesium (Na, K, Ca, Mg)

Exchangeable Na, K, Ca, and Mg were extracted using 1.0 M ammonium acetate solution at pH 7.0. Five grams of soil were shaken with 50 mL of the extracting solution for 30 minutes and filtered.

Sodium and potassium concentrations were determined using a flame photometer, while calcium and magnesium were determined using Atomic Absorption Spectrophotometry (AAS).

Determination of Available Phosphate (PO_4^{3-})

Available phosphorus was determined using the Bray-1 extraction method. Five grams of soil were extracted with Bray-1 solution and filtered. The filtrate was reacted with ammonium molybdate and stannous chloride to develop a blue color. Absorbance was measured using a spectrophotometer at 660 nm.

Determination of Sulphate (SO_4^{2-})

Sulphate content was determined using the turbidimetric method. Soil extracts were treated with barium chloride to form barium sulphate precipitate. The turbidity was measured using a spectrophotometer at 420 nm.

Determination of Ammonium (NH_4^+)

Ammonium nitrogen was determined using the indophenol blue method. Soil extracts were reacted with phenol and hypochlorite reagents under alkaline conditions. The developed blue color was measured spectrophotometrically at 640 nm.

Determination of Total Nitrogen (T.N)

Total nitrogen was determined using the Kjeldahl digestion method. Soil samples were digested with concentrated sulphuric acid in the presence of a catalyst. The digested solution was distilled, and the released ammonia was trapped in boric acid and titrated with standard hydrochloric acid.

Determination of Organic Carbon (O.C) and Organic Matter (O.M)

Organic carbon was determined using the Walkley–Black wet oxidation method. Soil samples were oxidized with potassium dichromate and concentrated sulphuric acid. Excess dichromate was titrated with ferrous ammonium sulphate.

Organic matter content was calculated by multiplying the organic carbon value by a factor of 1.724.

Acid Digestion for Heavy Metal Analysis (Fe, Cd, Pb, Cr, Mn, As)

One gram of each soil sample was digested using a mixed acid solution consisting of nitric acid, perchloric acid, and sulphuric acid. The mixture was heated on a hot plate until a clear solution was obtained.

After cooling, the digest was filtered and diluted to a known volume with distilled water. The concentrations of iron (Fe), cadmium (Cd), lead (Pb), chromium (Cr), manganese (Mn), and arsenic (As) were determined using Atomic Absorption Spectrophotometry.

Determination of Total Hydrocarbon Content (THC)

Total hydrocarbon content was determined using solvent extraction and spectrophotometric analysis. Ten grams of soil were extracted with n-hexane in a separatory funnel and shaken vigorously. The extract was filtered and concentrated.

The absorbance of the extract was measured using a UV–visible spectrophotometer at 420 nm. THC concentration was determined by comparison with calibration standards prepared from petroleum hydrocarbon stock solutions.

RESULTS

Table 7: Percentage inhibition (%) of shoot height, leaf number and leaf areas of *Indigofera tinctoria* sown in soil polluted with spent lubricating oil

Concentration of SLO (ml)	Shoot height	Leaf number	Leaf area
0	34.10	37	20.43
50	26.14	30	66.35
100	31.46	23	60.82
150	37.04	70	90.03
200	40.01	74	96.01

The percentage inhibition of shoot height, leaf number and leaf areas of *Indigofera tinctoria* sown in soil polluted with spent lubricating oil is presented in Table 7. It was observed that at 50ml and 100ml there was more inhibition in shoot height (26.14% and 31.46%) while less inhibition in shoot height (31.46% and 37.04%) was observed at 100ml and 150ml concentration. Leaf numbers were more inhibited at 50ml and 100ml (30% and 23%) less inhibited 150ml and 200ml (70% and 74%). Leaf area was more inhibited at 50ml and 100ml concentrations (66.35% and 60.82%) while less inhibition was observed at 150ml and 200ml (90.03% and 96.01%).

Table 2: Effect of spent lubricating oil (SLO) on the leaf area of *Indigofera tinctoria*

Concentration of SLO (ml)	Leaf area (cm^2)
0	25.10 ± 2.04^a
50	19.20 ± 1.07^b
100	10.93 ± 2.11^c
150	13.13 ± 0.65^c
200	3.07 ± 1.37^d

Values are means and standard error of 4 replicates P=0.05

The results for the effect of spent lubricating oil (SLO) on the leaf area of *Indigofera tinctoria* is shown in Table 2. There was a significant decrease in leaf area of *Indigofera tinctoria* as spent lubricating oil concentration increased from 0ml, 50ml, 100ml, 150ml and 200ml compared to control samples (0ml). The highest leaf area was recorded in control samples ($25.10 \pm 2.04cm^2$) while the smallest leaf area was recorded in 200ml SLO concentration treatment ($3.07\pm1.37cm^2$).

Table 3: Effect of spent lubricating oil (SLO) on shoot height (cm) of *Indigofera tinctoria*

of SLO (ml)	WK1	WK2	WK3	WK4	WK5	WK6	WK7	WK8
0	15.30 ± 0.13^{a}	13.30 ± 0.26^{c}	14.69 ± 0.08^{b}	14.76 ± 0.78^{a}	14.87 ± 1.21^{d}	15.37 ± 1.68^{a}	15.68 ± 1.88^{a}	16.33 ± 0.56^{a}
50	11.31 ± 0.19^{c}	10.81 ± 0.14^{a}	9.99 ± 0.39^{c}	12.67 ± 0.87^{ac}	10.85 ± 0.65^{c}	9.73 ± 1.13^{c}	11.09 ± 1.64^{b}	8.55 ± 1.35^{b}
100	11.31 ± 0.01^{c}	10.79 ± 0.26^{a}	9.23 ± 0.86^{c}	10.98 ± 0.44^{c}	8.18 ± 0.70^{b}	11.18 ± 0.67^{b}	8.88 ± 0.78^{c}	8.34 ± 0.54^{b}
150	8.13 ± 1.77^{c}	9.86 ± 0.06^{c}	10.18 ± 0.27^{a}	10.46 ± 0.38^{c}	10.46 ± 0.27^{c}	10.87 ± 2.55^{b}	10.88 ± 0.44^{c}	10.90 ± 0.18^{bc}
200	10.15 ± 0.17^{c}	9.40 ± 0.98^{ab}	9.49 ± 0.38^{c}	9.59 ± 0.28^{c}	6.17 ± 0.48^{ab}	9.18 ± 0.79^{c}	8.85 ± 1.02^{c}	9.25 ± 0.66^{b}

Values are means of four replicate ± S.E p=0.05

The effect of spent lubricating oil on shoot height of *Indigofera tinctoria* is presented in Table 3. There was a significant reduction in shoot height with increase in concentration of spent lubricating oil treatments. There was a significant decrease in shoot height of *Indigofera tinctoria* from 11.31±0.19cm to 10.15±0.17cm, 10.81±0.14cm to 9.40±0.98cm, 9.99±0.39 to 9.49±0.38, 12.67±0.87cm to 9.59±0.28cm, 10.85±0.65cm to 6.17±0.48, 9.73±1.13cm to 9.18±0.79cm, 11.09±1.64cm to 8.85±1.02cm and 8.55±1.35 to 9.25±0.66cm treated with 0ml, 50ml, 100ml, 150ml and 200ml concentrations of spent lubricating oil at week 1, 2, 3, 4, 5, 6, 7 and 8 respectively compared to control treatment (0ml) ($p<0.05$).

Table 4: Effect of spent lubricating oil (SLO) on leaf number of *Indigofera tinctoria*

Concentration of SLO (ml)	Weeks after application WK1	WK2	WK3	WK4	WK5	WK6	WK7	WK8
0	10.98 ± 0.02^{f}	10.88 ± 0.51^{a}	11.24 ± 0.61^{b}	11.99 ± 1.29^{c}	13.38 ± 2.11^{d}	15.04 ± 4.17^{a}	18.58 ± 4.68^{a}	21.33 ± 1.71^{a}
50	8.55 ± 0.17^{g}	8.53 ± 0.06^{b}	9.85 ± 0.94^{a}	9.77 ± 1.22^{a}	10.29 ± 1.67^{d}	10.93 ± 2.04^{e}	12.43 ± 2.61^{f}	17.74 ± 2.06^{a}
100	7.18 ± 0.18^{h}	7.99 ± 0.56^{c}	8.57 ± 1.50^{c}	8.88 ± 1.91^{a}	9.37 ± 2.55^{d}	10.02 ± 2.68^{e}	11.03 ± 3.04^{f}	11.22 ± 1.44^{b}
150	6.34 ± 0.19^{i}	7.53 ± 0.22^{c}	7.73 ± 0.29^{d}	8.14 ± 0.71^{b}	8.58 ± 1.11^{d}	8.77 ± 2.61^{c}	9.62 ± 2.18^{c}	10.33 ± 1.46^{b}
200	4.19 ± 0.29^{j}	5.38 ± 0.51^{d}	6.18 ± 0.55^{d}	6.69 ± 0.74^{d}	7.44 ± 0.96^{d}	7.44 ± 2.15^{bc}	7.98 ± 2.76^{d}	8.44 ± 0.36^{c}

Values are means of four replicate ± S.E p=0.05

Mean values with similar subscript alphabets down a column are not significantly different from each other.

The effect of spent lubricating oil (SLO) on leaf number of *Indigofera tinctoria* is presented in Table 4. There was a significant decrease in the leaf number of *Indigofera tinctoria* as the concentration of spent lubricating oil increased (0ml, 50ml, 100ml, 150ml and 200ml) ($P<0.05$). However, oil concentration treatment from week 1 to week 8 respectively.

increase in leaf number was observed as the week of application increased. Leaf number reduced from 8.55±0.17 to 4.19±0.29, 8.53±0.06 to 5.38±0.51, 9.85±0.94 to 6.18±0.55, 9.77±1.22 to 6.69±0.74, 10.29±1.67 to 7.44±0.96, 10.93±2.04 to 7.44±2.15, 12.43±2.61 to 7.98±2.76 and 17.74±2.06 to 8.44±0.36 at 0ml, 50ml, 100ml, 150ml and 200ml spent lubricating

Table 1: Effect of spent lubricating oil (SLO) on the chlorophyll content index of *Indigofera tinctoria*

Concentration of SLO (ml)	Chlorophyll content index
0	15.62±1.80[a]
50	15.61±1.82[a]
100	11.52±1.89[ab]
150	8.27±2.05[c]
200	4.88±1.94[d]

Values are means and standard error of 4 replicates P=0.05

The effect of spent lubricating oil (SLO) on the chlorophyll content index of *Indigofera tinctoria* is presented in Table 1. There was a significant decrease in chlorophyll content level of *Indigofera tinctoria* at 0ml, 50ml, 100ml, 150ml and 200ml concentrations of spent lubricating and control (0ml) while no significant decrease was observed in chlorophyll content at 50ml concentration and control (0ml). The highest chlorophyll content was recorded in control (15.61±1.82) while the lowest chlorophyll content was recorded in 200ml SLO concentration treatment (4.85±1.94)

Table 5: Effect of spent lubricating oil (SLO) on dry weight (g) partitioning in *Indigofera tinctoria*

Concentration of SLO (ml)	Leaf	Root	Stem
0	0.65±0.18[a]	0.63±0.15[a]	0.96±0.39[a]
50	0.46±0.14[b]	0.46±0.08[b]	0.86±0.17[b]
100	0.57±0.15[c]	0.54±0.12[c]	0.67±0.31[c]
150	0.27±0.15[d]	0.18±0.07[d]	0.28±0.14[d]
200	0.09±0.07[e]	0.18±0.08[de]	0.25±0.07[d]

Values are means of four replicate ± S.E (p=0.05)

The effect of spent lubricating oil (SLO) on dry weight (g) partitioning in *Indigofera tinctoria* is presented in Table 5. Result revealed that there was a significant reduction in leaf, root and stem of *Indigofera tinctoria* as spent lubricating oil treatment increased from 0ml, 50ml, 100ml, 150ml, 200ml and control (0%) ($p<0.05$). After treatment with spent lubricating oil at 0ml, 50ml, 100ml, 150ml and 200ml concentrations, leaf number reduced from 0.46±0.14 to 0.09±0.07, root number reduced from 0.46±0.08 to 0.18±0.08 while number of stem reduced from 0.86±0.17 to 0.25±0.07 respectively.

Table 6: Effect of spent lubricating oil (SLO) on fresh weight (g) partitioning in *Indigofera tinctoria*

Concentration of SLO (ml)	Leaf	Root	Stem
0	1.65±1.04[b]	1.45±0.45[b]	1.56±0.54[b]
50	0.61±0.29[a]	0.62±0.23[a]	0.96±0.38[a]
100	0.87±0.31[a]	0.67±0.18[a]	0.87±0.38[a]
150	0.28±0.12[a]	0.26±0.29[a]	0.27±0.16[a]
200	0.17±0.06[a]	0.25±0.12[a]	0.18±0.12[a]

Values are means of four replicate ± S.E ($p>0.05$)

The effect of spent lubricating oil (SLO) on fresh weight (g) partitioning in *Indigofera tinctoria* is presented in Table 6. Result revealed that there was a significant reduction in leaf, root and stem of *Indigofera tinctoria* as spent lubricating oil treatment increased from 0ml, 50ml, 100ml, 150ml,200ml and control (0ml) ($p<0.05$). After treatment with spent lubricating oil at 0ml, 50ml, 100ml, 150ml and 200ml concentrations, leaf number reduced from 0.61±0.29 to 0.17±0.06, root number reduced from 0.62±0.23 to 0.25±0.12 while number of stem reduced from 0.96±0.38 to 0.18±0.12 respectively.

Table 11: Bioconcentration factor values of heavy metals in *Indigofera tinctoria*

Concentration of SLO (ml)	Fe	Cd	Pb	Cr	Mn	As	Zn
0	1.12	1.02	0.64	1.02	1.21	1.43	0.98
50	1.58	1.73	1.77	1.72	1.68	1.69	1.71
100	1.54	1.56	1.64	1.63	1.58	1.66	1.61
150	3.15	3.18	3.23	3.17	3.18	3.21	3.12
200	2.60	2.61	2.64	3.08	2.62	2.73	2.63

Table 11 shows the bioconcentration factor values of heavy metals in *Indigofera tinctoria.* Iron ranged from 1.54 to 3.15mg/kg compared to control (1.12mg/kg), cadmium range from 1.56mg/kg to 3.18mg/kg compared to control (1.02mg/kg), lead range from 1.64 mg/kg to 3.23 mg/kg compared to control (0.64 mg/kg), chromium range from 1.63 mg/kg to 3.17 mg/kg compared to control (1.02 mg/kg), manganese range from 1.58 mg/kg to 3.18 mg/kg compared to control (1.21 mg/kg), arsenic range from 1.69 mg/kg to 3.21 mg/kg compared to control (1.43 mg/kg) and zinc range from 1.61 mg/kg to 3.12 mg/kg compared to control (0.98 mg/kg).

Table 8: Concentration of heavy metals in the leaves of *Indigofera tinctoria* sown in soil polluted with spent lubricating oil

Concentration of SLO (ml)	Fe	Cd	Pb	Cr	Mn	As	Zn
			Mg/kg				
0	0.43	0.33	0.11	0.17	0.22	0.09	0.54
50	9.12	1.29	0.92	1.19	2.93	0.42	2.47
100	11.00	0.33	0.78	1.42	2.01	0.44	2.07
150	13.42	0.31	1.20	1.76	2.17	0.57	3.53
200	21.18	0.65	2.62	3.61	6.17	0.96	7.12

Table 8 shows the concentration of heavy metals in the leaves of *Indigofera tinctoria* sown in soil polluted with spent lubricating oil. Fe, Cd , Pb, Cr, Mn, As and Zn were significantly accumulated at 200ml concentration (21.18mg/kg, 0.65mg/kg, 2.62mg/kg, 3.61mg/kg, 6.17mg/kg, 0.96mg/kg and 7.12mg/kg) respectively.

Table 10: Effect of spent lubricating oil on the physicochemical properties of soil sown with *Indigofera tinctoria*

0	5.04	0.74	1.60	0.91	1.08	0.04	0.19	0.23	0.25	0.14	1.82	2.46	0.84	0.45	0.07	0.35	0.79	51.98
50	5.48	1.05	1.97	1.15	3.84	0.08	0.26	0.37	0.29	0.19	1.59	1.82	0.51	0.35	0.06	0.36	0.67	76.52
100	6.21	2.16	3.67	2.18	4.45	0.18	0.39	0.41	0.32	0.24	1.55	1.48	0.29	0.31	0.03	0.44	2.05	160.73
150	7.83	2.21	5.03	2.41	5.31	0.21	0.56	0.48	0.35	0.28	0.78	1.84	0.27	0.18	0.14	0.58	3.21	219.48
200	8.21	3.01	7.56	3.64	5.67	0.27	0.76	1.17	0.42	0.37	0.68	0.89	0.17	0.23	0.20	1.28	3.86	304.10

Key:
E.C = Electrical conductivity, T.N = Total nitrogen, T.O.C = Total organic carbon, T.H.C = Total hydrocarbon content
P = phosphorus, K = potassium Mg = magnesium, Na= sodium, Ca = calcium, Fe = Iron,
Cr = Chromium, Pb = Lead, Cu = copper

The effect of spent lubricating oil on the physicochemical properties of soil sown with *Indigofera tinctoria* is presented in Table 10. There was an increase in pH content from 5.48 to 8.21 of the soil sample with increase in spent lubricating oil concentration compared to control (5.04). This indicated the soil was slightly acidic before being polluted with spent lubricating oil. The addition of spent lubricating oil made the soil less acidic and more alkaline. Phosphate level was observed to increase with increase in concentration of spent lubricating oil in the soil from 0.71mg/kg (0%) to 3.01mg/kg (200ml). There was also increase in Sulphate level with increase in concentration of spent lubricating oil from 1.97 to 7.56mg/kg compared to control samples (1.60mg/kg). Nitrate increase with increase in concentration of spent lubricating oil from 1.15mg/kg (50ml) to 3.64mg/kg (200ml) compared to control samples (0.91mg/kg). There was a significant increase in Iron content with increase in concentration of spent lubricating oil from 3.84 mg/kg (50ml) to 5.67 mg/kg (200ml) compared to control samples (1.08 mg/kg). There was also an increase in level of cadmium with increase in concentration of spent lubricating oil from 0.08mg/kg (50ml) to 0.27 mg/kg (200ml) compared to control samples (0.04 mg/kg). Lead level increased with increase in concentration of spent lubricating oil from 0.26 mg/kg (1%) to 0.76 mg/kg (200ml) compared to control samples (0.19 mg/kg). There was an increase in chromium level with increase in concentration of spent lubricating oilfrom

.37 mg/kg (50ml) to 1.17 mg/kg (200ml) compared to control samples (0.23 mg/kg). Manganese increased from 0.29mg/kg (50ml) to 0.42mg/kg (200ml) with increase in concentration of spent lubricating oil compared to control samples (1.25ml).

There was a significant increase in arsenic content with increase in concentration of spent lubricating oil from 0.19 mg/kg (50ml) to 0.37 mg/kg (200ml) compared to control samples (0.14 mg/kg). Sodium content decreased from 1.59 mg/kg (50ml) to 0.68 mg/kg (200ml) with increase in concentration of spent lubricating oil compared to control samples (1.82%). Potassium content decreased from 1.82 mg/kg (50ml) to 0.89 mg/kg (200ml) with increase in concentration of spent lubricating oil compared to control samples (140ml). Level of calcium decreased from 0.51 mg/kg (50ml) to 0.17 mg/kg (200ml) with increase in concentration of spent lubricating oil compared to control samples (37.5ml) Magnesium content decreased from 0.35 mg/kg (50ml) to 0.18 mg/kg (150ml) with increase in concentration of spent lubricating oil compared to control samples (25ml), There was an increase in total nitrogen and organic carbon contents of the polluted soil compared to control soil samples. This increase may be due to application of spent lubricating oil to the soil. Organic matter content increased from 0.36 to 1.28 with increase in volume of spent lubricating oil compared to control samples (0.35). Total hydrocarbon content increased from 76.52mg/kg (50ml) to 304.10mg/kg (200ml) with increase in spent lubricating oil when compared to control (51.98mg/kg).

DISCUSSION

Results obtained in this study showed that there was a significant reduction in plant height, number of leaves and leaf area in the oil polluted soil compared to the unpolluted soil (control). These results in agreement with previous reports of Adewumi *et al*. (2021) and Okebalama *et al*. (2024) for *Amaranthus hybridus* and *Phaseolus vulgaris* respectively. The data obtained for plant height, number of leaves and leaf area were significantly different ($p<0.05$) between oil treated plants and the control samples. The study agrees with the findings of Zhang *et al*. (2022) who recorded similar results caused by petroleum hydrocarbons in diesel fuel and inferred that the negative effects could be due to the impermeability effects of petroleum hydrocarbons or immobilization of nutrients especially nitrogen.

Indigofera tinctoria sown in non-polluted soul had the highest growth compared to those sown in polluted soil. At 50ml (control), shoot heights of *Indigofera tinctoria* was 16.31±0.55cm. There was a gradual decrease in the shoot height as the concentration of spent lubricating oil in the soil increased. The shoot height of *Indigofera tinctoria* at 3% concentration level was 10.46±0.27cm which represent a significant decrease from the control plant. This decrease in leaf number at different concentration level can be attributed to a host of factors including blockage of conducting tissues thereby preventing water and nutrient into the plant and limiting their ability to produce more leaves rapidly (Adeoye and Omolayo, 2023; Ogunjobi *et al*., 2021). However, the growth of the plant was not significantly affected at lower concentrations of 50ml and 100ml. At 150ml oil pollution, there was a gradual growth increase from the 6th week (10.87±2.55cm). This indicate that the ornamental plants can withstand low levels of spent oil pollution (Ibrahim *et al*., 2022).

Leaf number was significantly reduced in *Indigofera tinctoria* sown in the spent oil polluted soil when compared with the control treatment and the reduction followed an increase in oil concentration. The significant decrease in the number of leaves, shoot height and leaf area in plant at high oil concentration apparently reduced the photosynthesis rate of the plant and therefore a corresponding reduction in growth occurred. Root stress reduces leaf growth through adverse effects on stomata conductance Eze *et al*., 2021; Nwankwo *et al*., 2019).

The result of plant height agrees with the previous findings of Adeoye and Omolayo (2023) on the significant reduction of plant growth occasioned by oil pollution. This trend may be explained by the report of and Ogunjobi *et al*. (2021) which stated that immediately after an oil spill there is usually a horizontal migration of oil into soil horizons. Oily scum on soil surfaces would impede oxygen and water. It may also cause some toxic elements to be more available to plants thereby causing reduction in plant growth (Alabi *et al*., 2020). Okebalama *et al*. (2024) reported that spent lubricating oil in soil creates an unsatisfactory condition for plant growth ranging from heavy metal toxicity to insufficient aeration of the soil. Therefore, the general depression in growth is due to the adverse effect of oil. It was reported by Kyunghyun (2010) that crude oil in soil makes it unsatisfactory for plant growth. This was due to spaces by the oil. Ibrahim *et al*., (2022) also reported that plants growing in an oil polluted environment are generally retarded with chlorosis of leaves and dehydration of plant. The increase in the concentration of oil produced morphological changes in both plants such as necrosis, reduced growth and leaf droppings after

two weeks of treatment. Chlorosis was also noticed after 3 weeks of planting in soil polluted with spent lubricating oil (Adewumi *et al*., 2021; Eze *et al*., 2021; Zhang *et al*., 2022).

A reduction in chlorophyll content was observed in *Indigofera tinctoria* as concentration of oil increased. The chlorophyll content was highest in the 150ml pollution level. This indicated that the test plant grew under stress. This reduction kin chlorophyll level was similar to the findings by Zhang *et al*. (2021) where reduction in chlorophyll and protein levels was reported in *Amaranthus hybridus* grown in soil contaminated with spent lubricating oil. Ibrahim *et al*. (2022) also made similar observations on *Chromolaena odorata* sown in soil treated with crude oil. The result s of the present study, were a negative interaction existed between the soil lubricating oil contents and biomass accumulation in *Indigofera tinctoria* confirmed the reports of Adeoye and Omolayo (2023) who noted that as hydrocarbons from oil polluted soil accumulate in the chloroplast of leaves,, photosynthesis ability of the leave becomes reduced, affecting translocation in affected plants probably due to obstruction of the xylem and phloem vessels hence reduction in photosynthetic and matter contents. The chlorophyll content is always an indication of the level of physiological condition of a plant species (Alabi *et al*., 2020).

Various contaminants including crude oil, spent lubricating oil and heavy metals have been found to significantly affect the growth and performances of various plant species, photosynthetic activities occur in the leaves and in this present study, spent lubricating oil has caused significant reduction in the number of leaves and leaf area which will result in consequent reduction in surface area availability for photosynthesis hence reducing photosynthetic activities (Eze *et al*., 2021 and Ogunjobi *et al*., 2021). The reduction in leaf chlorophyll content of plants grown in soil polluted with spent lubricating oil has gave implications for photosynthesis.

The pH values of this study showed that the soil was slightly acidic but became less acidic as the concentration of oil increased. The decrease in pH as the level of oil concentration increased contradict the report of Zhang *et al*. (2022) who observed an increase in pH as the level of oil pollution increased. As shown in Table 10, soil pH varied from 5.01 to 8.21 in soil containing *S. alata*. This is consistent with the results of Okebalama *et al*. (2024). The soil pH serves as an index of availability of nutrients, the potency of toxic substances presents in the soil and the physical properties of the soil. Ibrahim *et al*. (2022) found that at pH values between 5 and 8 mineralization of hydrocarbons in estuarine sediments was highly dependent on oxygen availability.

The result of soil analysis obtained in this study showed an increase in the concentration of PO_4, SO_4, NH_4, Fe, Cd, As, Zn, Mn, Pb, and V in soil polluted by spent lubricating oil. The result of the plant analysis shows that Fe was significantly accumulated. A value of 21.17mg/kg was observed at the highest concentration (200ml). This indicates that heavy metal concentration increased as the concentration of the spent lubricating oil increased (Adeoye and Omolayo, 2023; Okebalama *et al*., 2024). The control (0ml) has the least value for Fe. Pb, taken by *Indigofera tinctoria* sown in soil polluted with spent lubricating oil was detected in the leaves of the plants examined at the control (0ml) and the highest concentration (200ml). The data obtained indicated that the leaves of *Indigofera tinctoria* contained 0.10mg/kg at 0% concentration and 2.61mg/kg at 200ml concentration. This shows that the plant is able to remediate a Pb contaminated soil and that the higher the concentration of pollution, the higher the concentration of heavy metal in the plant. Zhang *et al*. (2021) reported that soil Pb was taken up in substantial quantities by herbaceous and woody species grown in contaminated sites. Seventy percent of species tested contained higher root Pb compared to shoot Pb, indicating limited mobility once observed by the roots. In plants exposed to lead contaminated rooting media, the roots always contained lead concentration considerably greater than other above ground tissues. Lead is bound to the roots where such binding serves to protect the remaining plant parts from injury. Eze *et al*. (2021) reported an elevated metal concentration in plant tissues of *Ricinus communis* (castor oil) exposed to spent lubricating oil.

Cadmium, iron, chromium and zinc were found in the leaves of *Indigofera tinctoria* and they were found to increase in concentration as the concentration of the spent lubricating oil increased in the order Fe>Zn>Mn. High levels of Zn in soil inhibit many plant metabolic functions and result in the retarded growth and causes senescence. Zinc toxicity in plants limits the growth of both root and shoot (Ibrahim *et al*., 2022; Zhang *et al*., 2022). Zinc toxicity also cause chlorosis in the younger leaves, which can extend to older leaves after prolonged exposure to high soil Zn level. The regular limit of cadmium (Cd) in agricultural soil is 100mg/kg (Nwankwo *et al*., 2019). Plant grown in soil containing high levels of Cd shows visible symptoms of injury reflected in terms of choruses, growth inhibition, browning of root tips and finally death (Zhang *et al*., 2022).

Chromium (Cr) compounds are highly toxic to plant and are detrimental to their growth and development. Although some crops are not affected by low Cr concentrations, Cr is toxic to most higher plants at 100 mg/kg dry weight (Adeoye and Omolayo, 2023). Since seed germination is the first physiological process affected by Cr, the ability of a seed to germinate in a medium containing Cr would be indicative of its level of tolerance to this metal.

Iron is an essential element for all plants, it has many biological roles in the processes as diverse as photosynthesis, chloroplast development and chlorophyll biosynthesis. Iron toxicity in tobacco, soybean and *Hydrilla verticillata* are accompanied with reduction of plant photosynthesis and yield and the increase in oxidative stress and ascorbate peroxidase activity (Eze *et al*., 2021).

The organic C and N contents of the contaminated soils increased compared to the control. This resulted from the application of spent lubricating oil to the soil. Crude oil, from which the lubricating oil is produced, contains principal elements such as oxygen, nitrogen and sulphur other than hydrogen and carbon (Alabi *et al*., 2020; Zhang *et al*., 2022).

Similarly, the application of spent lubricating oil to the soil increased the contents of phosphate, nitrates, sulphates, iron, arsenic and zinc. They all increased as a result of the application of spent lubricating oil to the soil. Thus the soil contaminated soils contained more heavy metals than the control and the values increase with increase oil concentration. This implies that soil retains heavy metals from spent lubricating oil. The behavior may result from certain mechanisms such as chelation and sorption by soil. Ibrahim *et al*. (2022) reported that there is a bonding relationship between contaminants and soil surface due to sorption forces. However, it was observed that many of these heavy metals were present even in the control (0%) before contamination with the spent lubricating oil. The presence of metals in the uncontaminated soil indicates that heavy metals naturally occur in the environment and natural ecosystem (Okebalama *et al*., 2024). This further shows that they are natural components of the ecological system associated with one or more functions which may not be harmful at reduced concentration but could become toxic at heightened doses. Heavy metals have also been shown to affect the soil physically, ch chemically, biologically and microbial properties of soils (Eze *et al*., 2021).

The results showed a significant increase in the total hydrocarbon content (THC) with increased levels of spent lubricating oil pollution. Total extractable hydrocarbon content of soils is frequently used to assess and ascertain the extent of soil contamination (Adeoye and Omolayo, 2023; Ogunjobi *et al*., 2021). Several works have shown that high concentration of THC in soils is detrimental to the growth and productivity of plants (Zhang *et al*., 2022).

The results also showed a significant increase in the percentage organic carbon and organic matter content of spent lubricating oil polluted soil. Organic carbon and organic matter affect soil properties such as their water holding capacity, bulk density and mobilizes nutrient for plants. Ogunjobi *et al*. (2021) also reported that organic carbon and organic matter when present in sufficient quantity have beneficial effects on soil chemical and physical properties. Thus, the significant increase in organic carbon and organic matter content of the soil may have beneficial effect on the soil chemical and physical properties. This agrees with earlier reports of Adeoye and Omolayo (2023) which stated that organic carbon and organic matter content from wastes can influence the ability of microorganisms to degrade pollutants.

Soil contaminated with petroleum products have been shown to have large increase on nitrogen and phosphate content (Okebalama *et al*., 2024). The total nitrogen contents in the soil showed that it increased as the soil contamination increased in the soil. Hugh concentration of heavy metals in soil can negatively affect plant growth and yield as these metals interfere with metabolic functions in the plants including physiological and biochemical process, inhibition of photosynthesis and respiration (Eze *et al*., 2021). This indicates why there was a reduction in vegetative growth of *Indigofera tinctoria* used after oil has been applied to the soil. Chorosis, necrosis and stunted growth were observed in some of the leaves of the plants a different concentration but it was more obvious in the 150ml and 200ml concentration. Some of these symptoms have been attributed to zinc toxicity (Adewumi *et al*., 2021). The leaf choruses however started disappearing around the 5th week indicating that many of the organic compound have been transferred to the atmosphere. This observation agrees with the study of Eze *et al*. (2021) who observed similar disappearance of the chlorosis with time.

From the result obtained for bioconcentration factor, it was observed that there was an increase with increase in the concentration of spent lubricating oil. The values of the bioconcentration factor was low for all the heavy metals considered in the non-polluted samples compared to those polluted. Gradual accumulation and biomagnification of these heavy metals can rise to a dangerous or lethal level which could be a health hazard to man and his animals if ingested or consumed as food (Zhang *et al*., 2021) stated that metals contained in plant root can also translocate the accumulated metals from the root to the shoot of leaves. Metal concentration in plant tissues may indicate that the plant is capable of removing the metals from the soil matrix. It would also show that removed metals can be translocated from the roots to the shoots and leaves in a similar fashion as hyper-accumulators species.

The physical properties of oil imposed some stressful conditions, which may have interfered with water uptake and gaseous exchange (Adeoye and Omolayo, 2023). These conditions in turn result in physiological drought (Alabi *et al*., 2020). It was observed that the contaminated were clumped together and the pores in the soil must have been blocked. Soils polluted with spent lubricating oil result in the soil remaining unsuitable for crops growth and depending on the degree of contamination, types of soil and soil environment, the soil may remain unsuitable for crop growth for months or years until the oil is degraded to tolerable levels (Ibrahim *et al*., 2022).

CONCLUSION

This work has proved that *Indigofera tinctoria L.*. is an ideal plant for the phytoremediation of soil polluted with spent engine oil. The hydrocarbons and heavy metals from the spent engine oil were accumulated in the leaves, stems and roots of the plant. Spent engine oil did not have any adverse effect on the plant rather the plant degraded it and utilized it for growth. *Indigofera tinctoria* accumulated Fe, Cd, Pb, Cr, Mn, As, Zn, Na, K, Ca and Mg in the leaves, stems and roots. Therefore, the plant can be used as a hyper accumulator plant for bioremediation. In this way, these heavy metals are removed from the environment. With the spate of oil pollution going on in many parts of Nigeria especially in oil producing states and mechanic workshops, planting of this perennial shrub will not only decontaminate these pollutants but also aerate the environment during photosynthesis. Vehicle owners in Nigeria should avoid over usage of crankcase oil between each change to reduce the production of toxic PAHs and heavy metals with the devastating effect on living organisms. Bioaccumulation of hydrocarbons and heavy metals along food chain should be curbed through recycling of SEO rather than indiscriminate pouring into the environment.

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SENSORY EVALUATION AND PROXIMATE COMPOSITION OF CHIN-CHIN PRODUCED FROM BLENDS OF WHEAT AND PLANTAIN FLOURS

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ABSTRACT

The aim of this study was to produce and evaluate chin-chin products from composite flours using wheat and plantain flour blends. The unripe plantain was sun dried, the fingers of the unripe plantain (*musa paradisiaca*) were carefully detached from the bunch, sorted, cleaned, peeled and sliced and was milled and sieved. Chin-chin was produced from the three formulations: A (wheat 100% control), B (wheat and plantain 70:30%), and C (wheat and plantain 50:50%). Proximate composition and sensory evaluation were determined on the chin-chin samples. In proximate analysis, the result showed a trend that there was a significant difference ($p \geq 0.05$), that the ash, fibre, and carbohydrate increased from sample A to sample C as 1.04 to 1.12%, 1.21 to 1.37% and 83.72 to 86.36% respectively. In sensory analysis, the result showed a trend, that there was a significant difference ($P \geq 0.05$) for colour, texture, and general acceptability, with sample A rated highest as 5.00 to 3.70%, 5.00 to 4.00% and 5.00 to 4.40% while there was no significant difference ($P < 0.05$) for crispness, taste and aroma respectively. The results of this study shows that the formulated wheat composite flours were good sources of carbohydrate, fibre and ash but low in fat and protein. However, the sensory evaluation showed that the composite flour chin-chin was not rated high in colour, texture but still acceptable. It was therefore concluded that wheat and plantain will be good flour blend for the production of chin-chin.

KEY WORDS: Plantain, Wheat, Flour, Composite, Chin-chin

INTRODUCTION

Chin-chin is a fried snack popular in West African countries especially Nigeria. It is a sweet hard donut like fried product which is sometimes baked dough of wheat flour, with eggs and other ingredients (Akubor, 2004). The flour is mixed to form elastic dough which is properly kneaded, rolled and cut into desired shapes. The shaped flat dough is then deep fried in hot oil and when it is slightly gold brown, it is scooped out to let oil drain (Mepba *et a1*, 2007). This is usually served to visitors during parties and ceremony. Deep fat frying (DFF) or immersion frying is a cooking and drying process using a hot oil medium and is widely used in food preparation (Akubor, 2004). In this method oil is used for immersion at higher temperature above the boiling point of water. The temperature of the oil usually ranges from 130-200°C (Tangduangde *et al*., 2003). During frying, heat that is used to cook foods attacks the moisture and as the heat penetrates the food, moisture evaporates 1mm the surface of the food and it dries. Food with high moisture content such as starch repels oil absorption. The increased temperature of the oil and the decreased moisture content of the fried food cause many physical, nutritional and chemical changes such as browning, which is as a result of reaction between the sugar present in food and amino acid under high temperature (Millard reaction), gelatinization (swollen of starch under high temperature) and even de-maturation of protein present in that fried product. All these changes are dependent on the flying conditions: oil temperature, frying time, the oil type and the nature of the food to be fried (Cheevasanthianchioporn and Tangdaungdee, 2009). Chin-chin is a traditional Nigerian snack prepared using wheat flour, butter, milk arid eggs from which a stiff paste is made. It is deep-fried until golden brown and crispy. It is quite popular across Nigeria and in most of Western Africa countries. Chin-chin is sweet to taste, slightly hard and can be compared to a harder version of a doughnut and sometimes prepared by baking instead of frying (Adegunwa *et al.,* 2014). Wheat *(Trilicum* spp) has been the major cereal grain used in the bakery industry due to its gluten proteins to form viscoelastic dough required to bake leavened bread. These gluten proteins arc necessary for the production of the great variety of foods associated with wheat around the world. Chin-chin is a fried snack popular in West Africa. It is a sweet, cookie-like product made from wheat foul and egg (Akubor. 2004). It is usually kneaded and cut into small sizes prior to frying. Wheat flour is the main raw material and therefore there is need to enrich it with adequate protein and fiber sources. Plantain major group of banana varieties *(genus musa)* that are staple foods in many tropical areas. The edible fruit of plantain has more starch than the common desert banana and is not eaten raw. Because plantain, have the most starch before they ripen, they are usually coked green, either boiled or fried savory dishes. The ripe fruits coconut juice or sugar as a flavoring. Plantains may also be dried for later use in cooking or ground for use a meal; which can be further refined to a flour (Bayeri *et al,* 2011; Okwu and Okwu, 2004). Plantains are sometimes called green bananas, but they will turn yellow and then dark if allowed to ripen. Plantains are grown in South and Central America, Africa and Asia, where they are important food sources. Wheat *(triticum aestivums L)* is the most extensively grown cereal crop in the world, covering about 237 million hectares annually, accounting for a total of 420 million tons (Isitor et *al.,* 2010; Langer and hill, 2011; Olabanji *et al.,* 2004) and for at least one fifth of man's caloric intake (Ohiagan *et al.,* 2017). Wheat is an annual grass growing to between to 1meters in height, with a long stalk that terminates in a tightly formed cluster of plum kernels enclosed by a beard of bristly spikes (Smith, 2010). It is grown all *over* the world for its highly nutritious and useful grain, as one of the top three most produced crops, along with corn and rice. It is used in the production of bread, biscuits, doughnut feeds etc. Wheat is one of the most important staple food crops for humans. It provides about 20% of food, energy and protein worldwide. It is the most widely grown crop in the world with 225 million harvested in 2009.

As everybody including federal government is putting effort together to induce foreign exchange conservation by means of local material utilization, it has been decided to carry out work on plantain blend in order to use them to substituted for imported flours for baking. Although wheat flour is generally employed as the basic ingredient in confectionery manufacturer, it can only grow under certain climate conditions, consequently, industries in countries where wheat does not grow have to improve the grains or the flour. In Nigeria to be precise, a large sum of money is spent on importation, especially with the present rate of confectionary products and bakeries sin Nigeria. Success in this trend of supplementation will save a huge sum of money being spent on wheat importation and now could be used to improve other sectors of the country's economy. The aim of the study is to produce and evaluate chin-chin products from composite flours using plantain with the following objectives: to produce chinchin from wheat and locally source unripe plantain flours, to evaluate the sensory qualities of chin-chin produce from wheat flour and plantain flour blends, to determine the proximate composition of the processed sampled product and the utilization of plantain flour, a local material to produce chin-chin.

MATERIALS AND METHODS

(powder), milk flavour, baking powder, salt, vegetable oil, eggs, nut meg was used to improve the overall quality of the chip-chin. These ingredients were purchased from the same market. All other materials used was sourced from the Department Food Technology Department workshop, Auchi Polytechnic, *Auchi*.

Production of Unripe Plantain Flour

The fingers were carefully detached from the hunch, sorted, cleaned, peeled and sliced to about 5mm thickness. The sliced plantain was sun dried for weeks. The dried chips were milled using a hammer mill and sieved (300-400rpm). The milled flour, which its moisture content was 6.85% was sealed and stored in polythene bags until needed for baking.

Collection of Materials Unripe plantain was purchased from Jattu market, Jattu, Edo State, Nigeria. Other materials of known high quality such as wheat flour, margarine, sugar,milk

Formulation of Flour Blend Samples

The two types of flour (wheat and plantain) obtained was used to formulate composite flour. Three formulations of different proportion were prepared as follows:

A Wheat (100% control)
B Wheat: Plantain (70:30%)
C Wheat: Plantain (50:50%)

The formulations (A, B and C) were used in making chin-chin

Preparation of Recipes

The preparation of recipes was based on 100% wheat and plantain composite flours with the following ingredient as shown in the table.

Table 1: Preparation of recipes for chin-chin

Table 1: Preparation of recipes for chin-chin

Ingredients	A	B	C
Wheat %	100	70	50
Plantain %	0	30	50
Sugar (g)	82g	82	82
Margarine (g)	60	60	50
Water (g)	110	110	110
Milk flavour (g)	13	13	13
Milk powder (g)	25	25	25
Baking powder (ts)	1	1	1
Salt (g)	1	1	1

Production of Chin-Chin

Chin-chin was produced from the three formulations, where all ingredients were weighed accurately. The pre-weighed flour, sugar, margarine, baking powder, milk flavour, salt milk powder, eggs were mixed thoroughly and water was added and mix properly to make adequate dough, and the dough was kneaded to form a uniform sheet thickness. It was rolled on a flat rolling board, sprinkled with the same flour to form a uniform thickness using a wooden rolling pin. The sheet was cut according to the desired shape and sizes of chin-chin with a knife. Place the pan with oil on the burner to heat up the oil, after the oil is heated, frying starts, frying the chin-chin dough in batches making sure the pan was not crowded. After frying, it was allowed to cool for 30 minutes and the chin-chin were stored in airtight containers before further analysis.

Proximate Analysis

The proximate analysis was carried out according to the procedure described by Association of Official Analytical Chemist (AOAC, 2000).

Determination of Moisture Content This is a measure of the % moisture lost due to drying at a temperature of 105*°C.* 2g each of the chin-chin sample was weighed (W_1) into pre-weighed credible and placed into a hot drying oven at 105°C for 24 hours. The process of drying, cooling and weighing were repeated until a constant weight (W_2) was obtained and the weight loss due to moisture was obtained by the equation.

Hence % moisture $\frac{W_2-W_1}{W_2} = 100$

W1 = Initial weight of the food sample before drying

Determination of Crude Fat Content

The crude input content in each of' the chin-chin sample was extracted using Soxhlet extraction. The powder sample (2g) was weighed (W_0) into a porous thimble and covered with a clean white cotton wool. Petroleum ether (200cm^3) was poured into a 250cm^3 extraction flask, which was previously dried in the oven at 105°C and weighed (W_2). The porous thimble was placed into the Soxhlet and the rest of the apparatus was assembled. Extraction was done for 5 hours, the thimble was removed carefully and the extraction flask was placed in a water bath, so as to evaporate the petroleum ether and then dried in an oven at a temperature of 105°C to completely free the solvent and moisture. The flask was then cooled in a desiccator and reweighed (W_1). The percentage crude lipid was calculated using the equation below;

% Crude Fat $= \frac{W_1 - W_2}{W_0} \times \frac{100}{1}$

Where: W_0 = weight of sample, g

W_1 = weight of flask and oil, g

W_2 = weight of flask, g

Determination of Crude Protein Content

The sample (2g) was weighed along with 20cm^3 of distilled water into a Kjaldahi digestion flask. It was shaken and allowed to stand for some time. One tablet of selenium catalyst was added followed by the addition of 20cm^3 concentrated tetraoxosulphate (vi) acid. The flask was heated on the digestion block at 100°C for 4 hours until the digest became clear. The flask was removed from the block and allowed to cool. The content was transferred into 50cm^3 volumetric flask and diluted to the mark with water. An aliquot of the digest ($10cm^3$) was transferred into

icro-kjeldahi distillation unit. A conical flask containing $20cm^3$ of boric acid indicator was placed under the condense outlet. Sodium hydroxide solution ($20cm^3$, 40%) was added to the content in the kjeldahl flask, by opening the tunnel stopcock. The distillation started and the heat supplied were regulated to avoid sucking back. When all the available distillate was collected in $20cm^3$ of boric acid, the distillation was stopped. The nitrogen in the distillate was determined by titrating with 0.01M of H_2SO_4, and the end point was obtained when the colour of the distillate changed from green to pink. Crude protein is a measure of nitrogen in the sample. It was calculated by multiplying the total nitrogen content by a constant, 6.25.

Determination of Total Ash Content

This was a measure of the residue remaining after combustion of the dried sample in furnace at a temperature of 600°C for overweight. 2g of powdered chin-chin sample vas weighed (W_1) into pre-weighed empty crucible (W_0) and placed into a muffle furnace at 600°C for 18 hours. The ash was cooled in a desiccator and weighed (W_2). The weighed of the ash was determined by the difference between the samples, pre-weighed crucible and the ash in the crucible. The percentage ash was obtained

$$\% \text{ Ash Content} = \frac{W_1 - W_0}{W_2 - W_0} \times \frac{100}{1}$$

Where: W_0 = Weight of Empty Dish; W_0 = Weight of Empty Dish + Sample before ashing and W_0 = Weight of Dish + Ash

90 minutes in a muffle furnace. It was finally cooled in a desiccator and weighed again (W_2). The percentage crude fibre was calculated using the formula:

Where: W_2 = Weight of dried residue, g

W_1 = weight of ash + residue, g

W_0 = weight of sample, g

this is based on the assumption that proteins contain about 16%N which include both true protein and non-protein N and does not make a distinction between available or unavailable protein. The crude protein was calculated using equation

$$\% \text{ Crude protein} = \% \text{ N} \times 6.25$$

Where the nitrogen content of the sample is given by the formula below;

$$N = \frac{Tv \times Na \times 0.014 \times V_1}{G \times V_2} = 100$$

Where: Tv = Titre value of acid (cm^3) N_a = Volume of digest and distilled water used for diluting the digest ($50cm^3$) V_1 = Volume of aliquot used for distillation ($10cm^3$)

U = Original weight of sample used g

Determination of Crude Fibre Content

2g of powdered sample of chin-chin was weighed (W_0) into a $1cm_3$ conical flask. Water ($100cm_3$) and $20cm_3$ of 20% H_2SO_4 were added and boiled gently for 30minutes. The content was filtered through Whiteman No 1 filter paper. The residue was scraped back into the flask with spatula. Water ($100cm_3$) and $20cm_3$ NaOH was added and allowed to boil gently for 30 minutes. The content was filtered and the residue was washed thoroughly with hot distilled water, then rinsed once with 10% HCl and twice with ethanol and finally three times with petroleum ether. It was allowed to dry and scrap into the crucible and dried overnight at 105^0C in a hot air oven. It was then removed and cooled in a desiccator. The residue was weighed (W_1) and ashed at 600^oC for

$$\% \text{ Crude fibre} = = \frac{W_1 - W_2}{W_0} \times \frac{100}{1}$$

Determination of Carbohydrate content

The Calculation by difference method described by AOAC (2000) was used to calculate the % carbohydrate content: %Carbohydrate = 100% - % (Protein + Moisture + Fat + Fibre + Ash Content)

Sensory Evaluation

The sensory properties of the chin-chin were evaluated using ten semi-trained panelists consisting of staff and students of the Department of Food Technology, Auchi Polytechnic, Auchi, Nigeria. Sample were evaluated for crispness, colour, texture, taste, aroma and overall acceptability using Five-point Hedonic scale (where 1 = dislike extremely and 5 = like extremely). A sample from each blend was presented to the panelists. Each panelist was provided with. a glass of tap water to rinse the mouth between evaluation.

Statistical Analysis

Data from analysis of samples were subjected to one way analysis of Variance (ANOVA) using statistical package for social science (SPSS Version 20). Means were equated and separated using Duncan's new multiple range test (MDRT) and LSD) at *(≤0.05)* and the results were expressed as mean + standard deviation

RESULTS AND DISCUSSION

Results

The results of this study are shown in table 4.1 and 4.2 as follows:

Table 4.1: **Sensory evaluation of chin-chin produced from wheat anti plantain**

Samples	Parameters					
Colour	Crispness	Texture	Taste	Aroma	Accept bility	A
5.00^{a}±0.00	4.60^{a}±0.52	4.80^{a}±0.63	4.50^{a}±0.71	4.50^{a}±0.71	5.00^{a}±0.00	B
4.10^{b}±0.57	4.60^{a}±0.52	4.60^{a}±0.52	4.40^{a}±0.97	4.30^{a}±0.67	4.30^{a}±o.67	C
3.70^{b}±0.82	4.50^{a}±0.53	4.00^{c}±0.47	4.10^{a}±0.82	4.30^{a}±0.82	4.40^{b}±0.70	

Values with the same superscript in the same column are not significantly different (P<0.05). Values are presented as mean ± standard deviation.

Key:

Wheat (100%)
H Wheat (70%) Plantain (30%)
C Wheat (50%) plantain (50%)

Table 4.2 proximate composition of chin-chin in produced from wheat and unripe plantain flour

Parameters (%)	Sample		
A	B	C	Moisture
5.67^{b}±0.00	7.48^{a}±0.01	5.16^{c}±0.01	Ash
1.04^{b}±0.02	1.09^{a}±0.02	1.12^{a}±0.02	Fibre
1.21^{c}±0.01	1.34^{b}±0.02	1.37^{a}±0.02	Fat
1.97^{a}±0.02	1.86^{b}±0.02	1.73^{c}±0.02	Protein
8.53^{a}±0.01	6.73^{b}±0.03	5.47^{c}±0.01	CHO
83.72^{c}±0.02	83.63^{b}±0.03	86.36^{a}±0.03	

Values with the same superscript in the same row are not significantly different (P<0.05). Values are presented as mean ± standard deviation.

Key:

Wheat				(100%)
H	Wheat	(70%)	Plantain	(30%)
C	Wheat	(50%)	plantain	(50%)

Sensory Evaluation

The result in table 4.1 was expressed in mean ± standard deviations, this was statistical packages for social sciences (SPSS statistics 17.0). The table 4.1 is the sensory evaluation of composite flour chin-chin showed that there was a significant difference (P > 0.05) in colour, texture and general acceptability. In which sample A in colour was (5.00), sample B (4.10) and sample C (3.70), in texture sample A was (5.00), sample B (4.60) and sample C (4.00), in overall general acceptability sample A (5.00), sample B (4.30) and sample C (4.40), however there was no significant difference (P < 0.05) in crispness, taste and aroma. In the crispness sample A was (4.60), sample B (4.60) and sample C (4.50), but sample A and B have the best crispness. In taste sample, A (4.80), sample B (4.40) and sample C (4.10). In aroma, sample A was (4.50) sample B (4.30) and sample C (4.30). The result in table 4.1 showed that there was a wide acceptance of the 100% wheat chin-chin sample compare to the composite samples. The sample A which was (100%) wheat was rated best because these was no plantain added and it was the type of chin-chin consumers were used to. The sample B was rated second best because it was composed of (70%) wheat and. (30%) plantain and it had a nice taste and it was crispy, and there was a reduction in moisture content and it was acceptable while sample C was (50%) wheat and (50%) plantain, it was the sample with the lowest moisture content and it was crispy and also acceptable.

Proximate Composition

The result in table 4.2 of the proximate composition showed that there was a significant difference (P > 0.05) as more plantain flour was incorporated into the composite flour, there was increase in Ash, Crude fibre and carbohydrate content. On the other hand, 100% wheat chin-chin is higher in protein and fat content. The protein content of the composite flour formulations ranged from 8.53 - 5.47%. The high protein content in 100% wheat flour chin-chin is due to the gluten of wheat flour. These results showed that mixing plantain flour with wheat flour have a great influence on the proximate composition level of the resulting mixture content of formulated composite hours ranged from to 1.97%. The crude fibre of the formulated composite flours shows significant difference (P < 0.05) and range from 1.21 - 1.37%. These values are in accordance with the allowance levels of food crude of 1.6 -2.8% as reported by FAO (2006). The carbohydrate content of the formulated composite flour in the present study is within the range required for wheat flour for bread baking and weaning food mixtures which is between 60 - 90% dry weight basis.

CONCLUSION

The result of this study showed that the formulated composite flours of wheat and plantain flour are also good sources of carbohydrate, fat, fibre, ash and protein and therefore are good alternative and cheap source of energy for most people. However,

showed that the composite flour chin-chin is not rated high in colour, texture but still acceptable. This study will help to reduce the dependence on cereal crops in food security.

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EFFECTS OF COOKING METHODS ON THE SENSORY PROPERTIES, ANTINUTRITIONAL CONTENT AND PROXIMATE COMPOSITION OF PIGEON PEA *(CAJANUS CAJAN)*

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ABSTRACT

Three different cooking methods of pigeon pea were analyzed with a view to determine the proximate composition, antinutritional content and sensory evaluation of pigeon pea *(cajanus cajan).* Sample A was pressure-pot cooked on gas stove for 1 hour, sample B was open-pot cooked on gas stove for 1 hour 45 minutes while sample C was open-pot cooked using firewood for 2 hour 30 minutes. Analysis on proximate composition, antinutritional content and Sensory evaluations were carried out on the three samples. There was significant difference (P>0.05) in the proximate composition (%) of the samples as follows: Ash (1.42^{a}, 1.31^{b} and I .24^{c}), Fibre (2.25^{ab}, 2.81^{a} and 2.65^{b}), Fat (2.16^{a}, 2.12^{b} and 2.11^{b}), Protein (16.32^{b}, 16.11^{c} and 16.91^{a}) and Carbohydrates (71.82^{b}, 72.34^{a} and 70.25^{c}) for sample A, B and C respectively. There was significant difference (P>0.05) in the antinutritional content (%) for phytate, tannin and oxalate except for alkaloid and phenol. Sample C (0.28^{a}) has the highest while A (0.13^{c}) has the least phytate value. Sample C (0.10^{a}) has the highest while sample A (0.06^{c}) has the least tanin value. Sample C (0.02^{a}) has the highest while sample B (0.01^{b}) has the least oxalate value. There was no significant difference (P<0.05) for alkaloid (0.01) and phenol (0.02). There was significant difference (p>0.05) in the parameters evaluated for sensory evaluation for colour, texture, taste. The values for sensory evaluation for colour ranged from (8.90^{a}) for sample A, (8.40^{ab}) for sample B and (7.80^{b}) for sample C. Texture value ranged from (8.80^{a}) for sample A, (8.30^{ab}) for sample B and (7.80^{b}) for sample C. Taste value ranges from (8.80^{a}) for sample A, (7.90^{b}) for B and (7.90^{b}) for sample C. There was no significant difference (p<0.05) in the parameters evaluated for sensory evaluation for aroma and general acceptability. The result clearly showed that pigeon pea cooked with firewood retained the highest nutrient of protein while the sample that was cooked with pressure pot (sample A) had the most reduced antinutrients and was rated the best in the sensory evaluation.

KEY WORDS: Pigeon pea, proximate composition, sensory evaluation, pressure pot, gas stove

INTRODUCTION

Among legumes, Pigeon pea *(Cajanus cajan)* is predominantly grown and consumed in India. It belongs to family Leguminosae (Akande *et al.*, 2020). Numerous nodules are present on roots; these nodules contain Rhizobium bacteria, which fix atmospheric nitrogen. The flowers are self-pollinated but cross-fertilization may also occur to some extent. The fruit of the pigeon pea is a pod, each containing 3 to *5* seeds which are round or lens shaped (Bamidele and Akanbi, 2013). It is the second most important pulse in the country and also grown in some East African and south Asian countries. India is the largest producer (81.49 %) and consumer of pigeon pea in the world. Pigeon pea accounted for about 20% of the total production of the pulses in the country during the year 2000-2001. Other major pigeon pea producing countries are Myanmar (10.02*%),* Malawi (2.64%) and Uganda (2.60%). The productivity is highest in Uganda (1000 kg/ha) followed by Nepal *(875* kg/ha) and India (728 kg/ha) (Balogun, 2013). It is observed that pigeon pea is economically and nutritionally important legume as major source of proteins in poor communities of many tropical and subtropical regions of the world (Singh and Basu, 2012). Legumes represent a major source of nutrients, including valuable but incompletely balance protein, particularly in vegetarians' diet. It has been estimated that the total production of legume provides almost as much protein (20-30 %) to the world as wheat and over 50% more than rice or corn (Akande *et. al.*, 2020). In addition, legumes supply significant amount of energy through carbohydrates (60 - 70%), lipids (1 - 7*%),* dietary fibers and minerals (2 - 5%), also the legume oilseed contains reasonable levels of thiamine, riboflavin and niacin. In spite of the nutritional potential of the legumes, they are underutilized as food (Akporhonor *et al.*, 2016). Pigeon pee is of great importance in human nutrition in true aspect, yet, a lot of consumers are not aware of this information. Also, several works reporting the compositional evaluation and functional properties of pigeon pea in use in developing countries abound in scientific literature. However, much still needs to be done on the nutritional composition of pigeon pea in Nigeria. The aim of the study is to evaluate effects of cooking methods on the proximate composition, antinutritional properties, and sensory qualities of cooked pigeon pea with the following objectives: to cook the pigeon peas with three different cooking methods using pressure pot, fire-wood and gas cooker, analysis of the proximate composition of the three different samples to ascertain which of the methods would retain the nutrient, analysis of the antinutritional content of the three different samples to ascertain which of the methods would help to reduce the antinutrients and to evaluate the sensory properties of the three cooked samples to ascertain consumers' acceptability.

MATERIALS AND METHOD

Source of Materials

Dried seeds of pigeon pea *(cajanus cajan)*, firewood, pressure pot, gas stove and aluminum pot were bought from a local market, Uchi Market in Auchi, Edo State, Nigeria. The preparations of the samples were readily done in the Department Food Technology, Auchi Polytechnic, Auchi, Edo state, Nigeria.

Preparation of Samples

Pigeon pea was manually cleaned by removing the bad ones, stones, damaged and immature seed and divided into three portions. The first portion of 250g was washed with water and was pressure cooked using 750m1 of water for 1 hour and was labeled as Sample A (pressure-pot cooked on gas stove for 1 hour). The second portion of 250g of the pigeon pea was washed and cooked with 750ml of water using aluminum pot on a gas stove for 1 hour 45 minutes and was labeled as sample B (open-pot cooked on gas stove for 1 hour 45 minutes). Another third portion of 250g of the pigeon pea was washed and cooked with 750m1 of water using aluminum pot on a firewood for 2 hour 30 minutes and was labeled as sample C (open-pot cooked using firewood for 2 hour 30 minutes). The three samples (Sample A - C) were cooked within the stated times till they became soft in texture. The 3 samples were served for sensory evaluation and packaged and kept in plastic containers at room temperature for analysis of proximate composition and antinutritional properties.

roximate Composition

Determination of Moisture Content:
The moisture content was determined by AOAC (1990). The moisture content of each sample was determined by weighing 5g of the sample into an aluminum moisture can or a crucible. The sample was dried in the oven to a constant weight at 105°C.

% Moisture Content: (weight of Can + Sample) — (Weight of Empty Can) x 100
Weight of Sample

Determination of Protein Content

The crude protein content was measured Kjeldahl method according to the procedure. Concentrated H_2SO_4 (12m1) and 2 tablets of catalyst was put into a Kjedahl digestion flask containing l g of the sample. The flask was placed in the digester fume cupboard and switched on. The digestion was done for *45* minutes to obtain a clear colourless solution. The digest was distilled with boric acid, and 20% sodium hydroxide solution was automatically metered into it in the Kjectic 2200 distillation apparatus until distillation was completed. The distillate was then be titrated with 0.1M HCl acid until a violet colour formation indicating the end point. A blank was also determined

Crude Protein = (Titre Value of Sample— Blank) x 0.01 x 14.002 x *6.25* x 100
Weight of Sample 1

Determination of Fibre Content
Crude fibre was determined using the AOAC (1990). 2g of the sample was transferred into I litre conical flask. 100mI of sulphuric acid was heated at 100°C for 30 minutes while being stirred. The content was filtered with filter paper, then washed using hot distilled water until neutral. The residue was transferred into the conical flask containing the sample. The content was and weighed. The thimble was placed in the extraction chamber and 80ml hexane was added to extract the fat. The extraction was carried out and will last for 1 hour 40 heated for 30 minutes and ensuring that the level of was minted by the addition of distilled water. After 30 minutes, the content was filter thoroughly until its washing will no longer be alkali. The residue was introduced into an already dried crucible and was ashed at 600°C.

% Crude fibre = weight after drying – weight after ignition x 100% weight of sample

Determination of Ash Content

The ash content of the sample was determined by the AOAC method (1990). A silicon dish was heated at about 60°C, cooled in a desicator and weighed into the silicon dish and transferred to the furnace. The temperature of the furnace was allowed to reach *550°c* after placing the dish in it. The temperature was maintained until a whitish-grey is obtained indicating that all the organic matter content of the sample has been destroyed. The dish was brought out from the furnace and cooled in the dessicator and weighed. The % ash content was calculated as follows:

$$\% \text{ Ash Content} = \frac{C - A}{B - C} \times \frac{100}{1}$$

Where: A = Weight of Empty Dish; B = Weight of Empty Dish + Sample before Ashing and
C = Weight of Dish + Ash

Determination of Fat Content

Crude pot was extracted in a socket extractor with hexane and quantified gravimetrically as described by AOAC (1990). Ig of sample was weighted unto an extraction thim described by AOAC (1990). Ig of sample was weighted unto an extraction thimble and was topped with grease-free cotton. Before extraction will commence, the round bottom flask was washed, dried, cooled

minutes after which the fat was collected in the bottom flask was cooled in a dessicator.

$$\%\text{Crude Fat} = \frac{\text{Weight of Fat}}{\text{Weight of Sample}} \times \frac{100}{1}$$

Determination of Carbohydrate

The difference method described by AOAC (1990) was used to calculate the % carbohydrate content: %Carbohydrate = 100% - % (Protein + Moisture + Fat + Fibre + Ash Content)

Statistical Analysis

Statistical analysis may be defined as “analyzing the collected data for the purpose of summarizing information to make it more usable and making generalizations about a product based on a sample drawn from that product”. In the present study, the results were expressed as mean± S.D. (Standard Deviation) using SPSS 20.

Sensory Evaluation

The cooked pigeon pea from different cooking methods were coded and presented to a team of ten panelists who are familiar with the organoleptic properties of the food, The panelists scored the colour, taste, aroma, texture and the overall acceptability of the sample using a 9-point Hedonic scale, where the most acceptable variety was subjected to other cooking method.

RESULTS AND DISCUSSION

RESULTS

The results of the study are presented in table 4.1. 4.2 and table 4.3.

Table 1: Proximate Composition of Pigeon Peas cooked with Different Method

	Sample		
Parameter	A	B	C
Moisture	$3.63^{b} \pm 0.03$	$13.20^{c} \pm 0.01$	$3.80^{a} \pm 0.01$
Ash	$1.42^{a} \pm 0.02$	$1.31^{b} \pm 0.01$	$1.24^{c} \pm 0.02$
Fibre	$2.25^{ab} \pm 001$	$2.81^{a} \pm 0.02$	$2.65^{b} \pm 0.01$
Fat	$2.16^{a} \pm 0.02$	$2.12^{b} \pm 0.02$	$2.11^{b} \pm 0.01$
Protein	$16.32^{b} \pm 0.03$	$16.11^{c} \pm 0.01$	$16.91^{a} \pm 0.02$
CHO	$71.82^{b} \pm 0.03$	$72.34^{a} \pm 0.04$	$70.25^{c} \pm 0.04$

*Values with the same superscript in the same row are not significantly different (p<0.05)
*Values are presented as mean ± standard
Values with the same superscript in th same row are not significantly different (p<0.05)

*Values are presented as mean ± standard deviation

Table 2: Antinutritional Contents of Pigeon Peas Cooked with Different Methods

Parameters (%)	Samples		
	A	**B**	**C**
Phytate	$0.13^{c} \pm 0.01$	$0.16^{b} \pm 0.01$	$0.28^{a} \pm 0.01$
Tannin	$0.06^{b} \pm 0.01$	$0.08^{b} \pm 0.02$	$0.10^{a} \pm 0.01$
Oxalate	$0.01^{ab} \pm 0.01$	$0.01^{b} \pm 0.00$	$0.02^{a} \pm 0.01$
Alkaloid	$0.01^{a} \pm 0.00$	$0.01^{a} \pm 0.00$	$0.01^{a} \pm 0.00$
Phenol	$0.02^{a} \pm 0.01$	$0.01^{a} \pm 0.01$	$0.02^{a} \pm 0.00$

*Values with the same superscript in the same row are not significantly different (p<0.05)

*Values are presented as mean ± standard deviation.

Table 3: Sensory Evaluation of Pigeon Peas with Different Cooking Method Samples

	Parameter				
Samples	**Colour**	**Texture**	**Taste**	**Aroma**	**Acceptability**
A	$8.90^{a}\pm0.32$	$8.80^{a}\pm0.42$	$8.80^{a}\pm0.42$	$8.20^{a}\pm0.92$	$8.70^{a}\pm0.67$
C	$8.40^{ab}\pm0.70$	$83.0^{ab}\pm0.67$	$7.90^{b}\pm1.20$	$7.90^{b}\pm1.20$	$7.70^{a}\pm1.49$
B	$7.80^{b}\pm1.03$	$7.80^{b}\pm0.79$	$7.90^{b}\pm1.00$	8.10^{b} ±0,80	$8.10^{a}\pm 1.00$

- ❖ Values with the sample superscript in the same column are not significantly different (p<0.05)
- ❖ Values are mean ± standard deviation.

KEY:

A = pressure-pot cooked on gas stove for 1 hour.

B =open-pot cooked on gas stove for 1 hour 45 minutes.

C = open-pot cooked using firewood for 2 hour 30 minutes.

DISCUSSION

The result as shown in table 1 reveal the proximate composition of three samples with three different cooking methods of pigeon pea. There was significant difference (p>0.05) in the moisture content of the samples. Sample B has the highest moisture content ($13.20^{c} \pm 0.01$) while sample A and C has the least moisture content. There was significant difference (p>0.05) in the ash, crude fibre, protein, fat and carbohydrate. However, sample A has the highest Ash content ($l.42^{b}\pm0.02$) while sample C has the least Ash content ($1.24^{a}\pm0.0l$). This was in agreement with Amarteiflo *et al.*, (2002). Sample C has the highest fibre content ($2.81^{a} \pm 0.02$) and sample A has the least fibre content ($2.25^{ab}\pm0.01$). Sample A has the highest fat content ($2.16^{b}\pm0.02$) while sample C has the least fat content (2.11±0.01). The work was reported by Bamigboye (2015*)*. Sample C has the highest protein content ($16.9l^{a}\pm0.02$) while sample B has the least protein content ($16.11^{a}\pm0.01$). Sample B has the highest carbohydrate content ($72.34^{a}\pm0.04$) while sample C has the least carbohydrate content. This was in agreement with Adeparusi (1994). The results revealed that the traditional method C (sample C) retained highest value of protei

he result of the antinutritional content of pigeon pea is shown in table 4.2. Antinutritional content of three samples with three different cooking methods of pigeon pea shows that there was significant difference(P>0.05) in the phytate content of the samples. Sample C (0.28°+0.01) has the highest phytate content because the cooking method that was used which is firewood has the lowest level for reduction of antinutrient in terms of phytate while sample A (0.13"±0.01) has the least value because, the cooking method that was used which is pressure pot on gas stove has the highest reduction of antinutrients in terms of phytate. Among all the antinutrients phytate is of major concern in human nutritio, particularly in infant nutrition (Kumar et al., 2010). This is related to its high chelating nature that affects protein and mineral bioavailability (Bora, 2014). There was significant difference (P>0.05) in the Tannin content, sample C ($0.10^a \pm 0.01$) (has the highest tannin content because the cooking method that was used which was firewood has the lowest level of reduction of antinutrients in terms of tannin while sample A ($0.06^b \pm 0.01$) had the least tannin content because the cooking method that was used which is pressure pot has the highest level for reduction of antinutrients in terms of tannin. Tannins has the ability to precipitate protein from aqueous solution. Tannins binds to protein making them bio-unavailable. There was significance difference (P>0.05) in the oxalate content.

Sample C ($0.02^a \pm 0.01$) has the highest oxalate content because the cooking method which is firewood has the lowest level of reduction of antinutrients in terms of oxalate while sample A ($0.01^{ab} \pm 0.01$) had the least oxalate content because the cooking method which is pressure pot had the highest level for reduction of antinutrients in terms of oxalate. Oxalate tends to render calcium unavailable by binding to the calcium ion to form complexes. The insoluble calcium oxalate may precipitate around soft tissues like kidney, causing kidney stones (Oke, 1986). There was no significant difference (P<005) in the alkaloid content. The three samples (sample A, B, and C) had the same alkaloid content ($0.01^a \pm 0.00$). Most alkaloids taste bitter to humans and because bitter taste is synonymous to noxious food, they are generally rejected. There was no significant difference (P<0.05) in the phenol content but sample A value still had A ($0.02^a \pm 0.01$) while sample B ($0.01^a \pm 0.01$) had the least Phenol content. Many phenolic compounds in plants are good source of natural antioxidants. Phenolic compounds in foods have inhibiting effects on mutagenesis and carcinogenesis (Hulse, 2017). However, the pressure pot cooked (sample A) had drastically reduced moat of the antinutrient in the pigeon peas.

The evaluation of the sensory attribute on the effect of cooking method is important for the determination of its acceptable cooking method. The result in Table 4.3 of the sensory evaluation revealed that in colour, there was no significant difference (p<0.05) observed among the samples. However, sample A ($8.90^a \pm 0.32$) has the highest mean value. The result for texture shows that there was significant difference (p>0.05) among the samples. Sample A (8.80a±0.42) was most preferred in terms of texture, sample B and C were least preferred. For taste, significant difference ($p>0.05$) was observed among the samples. Sample A with mean value of $8.80^a \pm 0.42$) was most preferred. Samples B ($7.90^a \pm 1.00$) and Sample C ($7.90^a \pm 1.20$) were least preferred in terms of taste. In terms of aroma, there was no significant difference ($p<0.05$) observed among the three samples. The result for aroma showed that sample B has mean value of ($8.70^a \pm 0.67$) was most preferred while sample A and B were least preferred.In terms of general acceptability, there was no significant difference ($p<0.05$) observed, the three samples were generally accepted. However, the pressure pot cooked pigeon peas had the highest rating sensory properties.

CONCLUSION

The research work showed that pigeon pea cooked with pressure pot had high sensory quality and also had reduced antinutrients while the pigeon pea cooked with firewood retained more nutrients in terms of protein. This study is recommended for enlightenment as the pressure-pot cooked on gas stove for 1 hour is more advantageous than the traditional open-pot cooked using firewood for 2 hour 30 minutes.

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MXENE FOR FLEXIBLE ELECTRONICS, WEARABLE DEVICES AND SMART SENSORS: A REVIEW

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ABSTRACT

MXenes, a class of two-dimensional transition metal carbides and nitrides, have emerged as promising materials for flexible electronics, wearable devices, and smart sensors. Since the discovery of Ti_3C_2Tx, MXenes have attracted significant attention due to their high electrical conductivity, hydrophilic surfaces, tunable surface terminations, mechanical flexibility, and solution processability. These features make them well suited for deformable and biointegrated systems. This review work discussed the most common method used to synthesize this class of materials , which is the etching method from MAX phases. This serve as the 3D bulk precursor of MXenes .The hexagonal crystal structure, properties and the challenges such as, susceptible to oxidation in ambient environments, lack of standardized characterization methods and regulatory guidelines for MXene-based materials and the hazardous nature of HF used were also discussed. The paper also examined ways of mitigating these challenges, which is for researchers to explore cost effective synthesis method of production and fabrication techniques

KEYWORDS: MXene, synthesis technique, flexible and wearable electronics, MAX phase, etching

method

INTRODUCTION

The continuous advancement of flexible and wearable electronic technology has opened new possibilities in personalized healthcare, soft robotics, smart textiles, and human–machine interaction systems. Unlike traditional rigid silicon-based devices, modern electronic platforms require materials that can simultaneously deliver high electrical conductivity, mechanical flexibility, lightweight characteristics, and durability under repeated deformation. Conventional conductive materials such as indium tin oxide (ITO), metal thin films, and silicon substrates are inherently brittle and prone to mechanical failure, limiting their applicability in deformable and wearable systems. As a result, the development of novel multifunctional materials suitable for flexible electronics has become a major research priority.

The emergence of two-dimensional transition metal carbides/nitrides (MXene) has attracted extensive research interest. With a unique two-dimensional layered structure, MXene has a large specific surface area, excellent electrical conductivity, high mechanical strength and good stability, which make it highly promising in hydrogen storage and catalysis (Runize & Wei, 2025). Nanomaterials are materials with at least one dimension in the nanoscale range (1–100 nanometers)**,** where they exhibit unique physical, chemical, and biological properties that differ from their bulk counterparts (Bhushan, 2017). The nanoscale size results in a hi gh surface-are to-volume ratio, which significantly enhances reactivity, strength, electrical conductivity,and optical characteristics (Kumar et al., 2021). The properties of nanomaterials are largely influenced by quantum effects, which become pronounced at such small dimensions. These effects can alter electrical, optical, and magnetic behaviors compared to the same material in bulk form (Wang et al., 2019).

Among emerging two-dimensional (2D) materials, MXenes—a class of transition metal carbides, nitrides, and carbonitrides have attracted significant attention for flexible electronic and smart sensing applications. Since their initial discovery in 2011, MXenes, particularly $Ti_3C_2T_x$, have demonstrated exceptional properties including metallic-level electrical conductivity, hydrophilic surfaces, adjustable interlayer spacing, and excellent mechanical compliance (. The presence of surface functional groups such as –O, –OH, and –F allows effective chemical modification and strong interfacial bonding with polymers, biomolecules, and other nanostructures. These characteristics make MXenes highly adaptable for composite-based flexible devices (Shah et al., 2023). Their preparation process makes the surface of MXenes rich in functional groups, and their unique accordion-like appearance endows MXenes with attractive electronic, optical, and magnetic properties, which can draw inspiration in energy storage (Xin et al., 2020)

MAX-phases are ternary carbides or nitrides with a general formula $M_{n+1}AX_n$, where n = 1, 2, 3; M is an early transition metal, A is an A-group element and X is carbon or nitrogen. These compounds have a hexagonal structure and are divided into several classes depending on the MAX-phase coefficient n:M_2AX (2 1 1) M_3AX_2 (3 1 2); M_4AX_3 (4 1 3). Typical representatives of the MAX phases are ternary carbides of the Ti-Al-C system. For the first time, titanium aluminum carbide Ti_3AlC_2 was synthesized in 1994 by sintering of a compressed mixture of TiAl, Al_4C_3 and carbon powders at 1500 °C for 20 h under argon atmosphere . The crystal lattice of Ti_3AlC_2 was found to be hexagonal with the unit cell parameters a = 0.30753 nm, c = 1.8578 nm and theoretical density of 4.25 g/cm^3 (Kvashina et al., 2020)

During the fabrication of MXene from MAX phases, a wide variety of negative functional groups are induced on the MXene surface, which is why, aggregation occurs in MXene suspension due to the van der walls interaction between these polar groups. Furthermore, the structural stability of pure MXene-based electrodes during the cyclic performance may be hampered due to there stacking nature of MXene. Additionally, $Ti_3C_2T_x$ may be partially oxidized by oxygen or water molecules into the nonconductive titanium dioxide (TiO_2), decreasing the redox reaction active sites and raising the charge transfer impedance. (Kvashina et al., 2020). Scientists are trying to solve these flaws by preparing MXene-based hybrid materials to enhance their capacitive characteristics. To overcome these drawbacks, scientists took the advantages of wide surface terminating groups of MXenes, that allows MXene materials to interact with other active material. This interaction increases the interlayer spacing of MXene by avoiding the aggregation problem for enhanced.

MXene is modified according to the demand and the structure optimization. Different structures have different effects on its electrochemical, photothermal, and microwave absorption properties, and its hydrophilic and hydrophobic characteristics. Exploring the properties of MXene, such as friction, adhesion, conductivity, and photothermal conversion, helps to expand its application fields. For surface modification, the interface between different components of most composite materials is connected through physical interactions (hydrogen bond, van der Waals force, etc.) with poor mechanical properties (Li et al., 2022)

The structure of MXenes is conducive to the improvement of the electrochemical performance of electronic devices. Electronic devices based on MXene materials can be assembled in the human body and work together, or they can be attached to the human body and work alone (Ruipeng et al., 2024).

The aim of this paper is to explore the applications of MXene-based materials in flexible electronics, wearable devices, and smart sensors, focusing on their unique structural, electrical, and surface properties that enable high performance and multifunctionality. The study highlights recent advancements in MXene synthesis, surface functionalization, and device integration, emphasizing their role in enhancing sensor sensitivity, flexibility, and durability. By reviewing current developments and identifying key challenges, this paper seeks to provide a comprehensive perspective on the potential of MXenes to advance next-gene/ration which ion transport between the MXene based hybrids is wearable and flexible electronic technologies

MXENE STRUCTURE

MXenes is the denomination of several transition metal carbides, nitrides or carbonitrides tipically obtained by chemical delamination of 3D ternary (or quaternary) compounds known as MAX phases. However, MXenes can also be obtained from other layered compounds, such as $Zr_3Al_3C_5$ and Mo_2Ga_2C. MXenes have as general formula $M_{n+1}X_nT_x$ (n = 1–3), where M represents a transition metal (such as Sc, Ti, Zr, Nb and others), X is carbon and/or nitrogen and T_x represents the hydroxyl, oxygen or fluorine terminations derived from the synthesis procedures (Rodrigo et al., 2019)

MXenes belong to the hexagonal crystal system and the $P6_3/mmc$ space group, the same as MAX phases. In MAX phases, the transition metal (M) and carbon–nitrogen (X) atoms are covalently bonded to form the M_6X octahedra, with the X atoms positioned at the center . The M atoms are hexagonally close-packed (HCP), while the A atoms occupy the interstitial spaces . These A atoms have weaker bonding energy than M and X atoms, making them easier to remove chemically through selective etching. During this process, the covalent M-X bonds remain intact, but new surface terminations (-OH, -O, -F) are introduced, compressing the structure and r esulting in a 2D HCP structure layered configuration . Conventional studies often overlook surface defects and assume uniform distribution of T terminations. $M_{n+1}X_nT_x$ has three types of structure as shown in figure 1

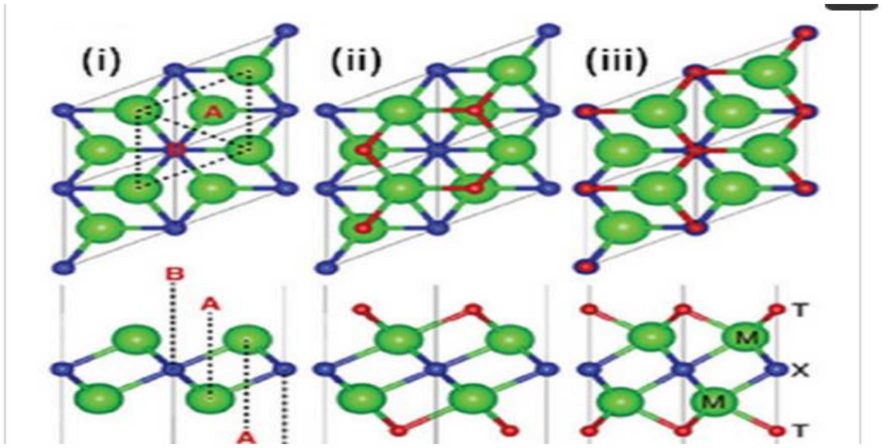


Figure 1. Structures of: (**i**) M_2X, (**ii**) M_2X-1, (**iii**) M_2X-2 for functionalized MXenes (Palledino & Baino, 2025)

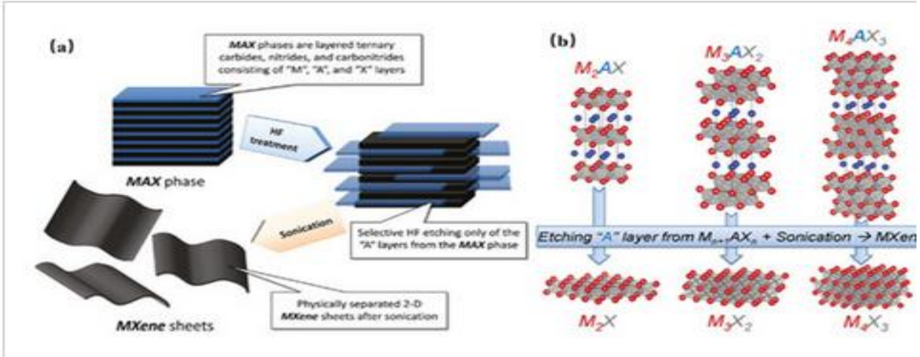
Theoretical calculations predict the possibility to obtain about 100 stoichiometric structures, from which approximately 20 different compositions have been synthesized experimentally . Some of the most studied materials of this class are Ti_3C_2, Ti_2N, Nb_4C_3, Nb_2C, and V_4C_3 (Maksym et al., 2021)

SYNTHESIS TECHNIQUE

Generally, top-down approaches are used to synthesize MXenes, in which the A-layer element is selectively etched from a MAX phase using hydrofluoric acid (HF) or in situ-generated etchants, such as LiF–HCl. , HF-Based Chemical Etching, first introduced by Naguib et al. (2011), concentrated hydrofluoric acid is used to etch out Aluminum (Al) from Ti_3AlC_2 MAX phase: The resulting MXenes are multilayered structures with −OH, −F, and −O functional groups. Among these, LiF–HCl can be adjusted under milder conditions than the others and forms larger, more stable flakes suitable for coatings. , However, in these traditional methods, hazardous and toxic fluoride-containing reagents are often used. As a result, they limit large production volumes. To address these challenges, safer and more scalable synthesis techniques have been developed. Although bottom-up strategies such as chemical vapor deposition (CVD) and molten salt synthesis are less explored than top-down methods, they offer promising alternatives with precise control over surface termination. The Lewis acidic molten salt method has an advantage as it can be applied to numerous MAX materials. Due to its universal and easy etching procedure, large-scale production is possible. It also provides better control of surface terminal groups and ensures metal nanoparticles can deposit uniformly. − Unfortunately, both of these are very complex procedures, and their high cost is a significant concern. Another innovative technique for producing MXenes free of fluorine is the mechanochemical route. With etchant NH_4HF_2, a new ultrafast Low-Temperature Molten Salt (LTMS) has recently been developed

that can produce various MXenes within minutes and generate more than 100g of $Ti_3C_2T_x$ in a single reaction. Furthermore, a molten salt-shielded synthesis (MS^3) method is capable of rapid synthesis of MXenes in open air, using Lewis-acid salts as etchants (Nishat et al., 2025)

The most common method used to synthesize this class of materials is the etching method from MAX phases, which serve as the 3D bulk precursor of MXenes as show in .Figure 1 above



Fgure 2. (**a**) Etching method from MAX phases (**b**) generation of different types of MXenes (Palladino & Baino, 2025)

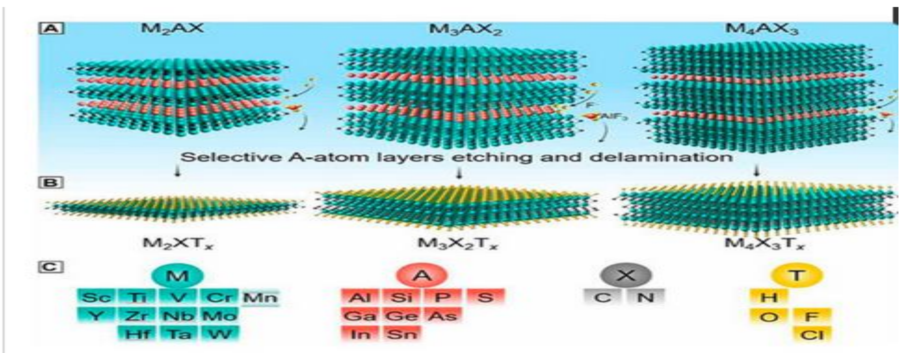


Figure 3. (**A**) MAX phases; (**B**) MXenes result from etching MAX phases; (**C**) M, A, X elements (Palladino & Baino, 2025)

Surface Chemistry and Tunability

MXenes can be modified and controlled to achieve desired surface chemical properties and functionalities. This tunable surface chemistry is enabled by their terminal groups (−OH, −O, −F), which also significantly influence interactions with other materials, such as polymers or textiles. One significant advantage of these surface terminations is that they can be controlled during or after synthesis with slight modifications, allowing tailored

functionalization. − However, MXenes made using traditional methods face challenges in enabling postsynthetic modifications because of strong chemical bonding between surface metal atoms and oxygen or fluorine. It is established that the surface chemistry of MXenes plays a paramount role in their properties and interactions, where O-terminated MXenes higher reactivity and adsorption capacity compared to other terminated groups (F– or Cl−). By controlling these surface terminations, the performance of MXene in applications such as energy storage, gas sensing, and catalysis can be enhanced (Nishat et al., ,2025)

Surface Functionalization Strategies of MXene

Surface functionalization plays a crucial role in enhancing the suitability of MXenes for flexible electronics and wearable devices. MXenes possess a general formula of $M_{n+1}X_nT_x$, where T_x represents surface terminations such as –O, –OH, and –F that are introduced during selective etching of MAX phases (Anasori & Gogotsi, 2023). These surface groups significantly influence electrical conductivity, hydrophilicity, interlayer spacing, mechanical flexibility, and chemical reactivity, which are essential properties for wearable and flexible systems.

One important strategy involves controlling surface terminations through etching chemistry modification. For example, replacing traditional HF etching with minimally intensive layer delamination (MILD) or fluoride-free etching methods allows better control of –O and –OH terminations, improving electrical conductivity and stability (Shah et al., 2023). Increased –O termination has been associated with enhanced conductivity and electrochemical activity, which is beneficial for flexible sensors and energy storage components in wearable platforms.

Another approach is surface modification via polymer grafting or composite formation. MXenes are highly hydrophilic, enabling strong interfacial bonding with polymers such as PDMS, polyurethane, and hydrogels. This improves mechanical robustness, flexibility, and stretchability while preserving conductivity (Li et al., 2022). Polymer–MXene composites are widely used in strain sensors and electronic skins because they combine mechanical compliance with high signal sensitivity.

Intercalation engineering is also widely employed. The insertion of organic molecules, metal ions, or small organic spacers between MXene layers increases interlayer spacing, prevents restacking, and enhances mechanical deformability and ion transport (Shah et al., 2023). This is particularly valuable for breathable textile-integrated devices and flexible supercapacitors.

Additionally, surface oxidation control and passivation strategies are critical for wearable applications, since MXenes are prone to oxidation under ambient conditions. Surface coatings, antioxidant additives, or encapsulation layers improve long-term environmental stability without compromising electrical performance (Li et al., 2022).

Overall, surface functionalization strategies—including termination control, polymer hybridization, intercalation engineering, and stability enhancement—significantly improve the mechanical flexibility, conductivity, environmental stability, and biocompatibility of MXenes

These modifications are essential for advancing MXene-based smart textiles, health-monitoring sensors, and next-generation flexible electronic systems.

PROPERTIES OF MXENE

MXenes possess several properties that make them highly attractive for flexible and wearable applications:

Mechanical Properties

MXenes exhibit outstanding mechanical properties, including remarkable flexibility, high tensile strength, and significant flexural rigidity. The Young's modulus of a $Ti_3C_2T_x$ monolayer has been calculated to range between 0.33 TPa and 0.03 TPa, making it the highest among all 2D materials, including graphene oxide (GO). Notably, the flexibility of $Ti_3C_2T_x$ is impressive: it has been reported that a $Ti_3C_2T_x$ film can support up to 4000 times its weight without experiencing any shape distortion or structural damage (Palladino & Baino, 2025)

The elastic behavior of MXenes is strongly influenced by their surface terminal groups. Specifically, the strength and length of surface bonds play a key role in determining their mechanical properties. Experimental studies indicate that MXenes with O-terminal groups are the most suitable candidates for applications such as supercapacitors and structural materials due to their exceptional flexibility. The Ti-O bond is notably stronger than the Ti-OH and Ti-F terminations . Density Functional Theory (DFT) simulations conducted on Ti_3C_2 and Ti_2C with different surface terminations have demonstrated that shorter bond lengths—such as those associated with oxygen groups—indicate stronger contacts, whereas F and OH bonds, being longer, result in weaker interactions(Palledino & Baino, 2025)

Regarding Ti-C bonds, previous studies have shown that Ti_2C, Ti_3C_2, and Ti_4C_3 MXenes exhibit considerable rigidity. However, graphene remains a superior alternative due to its higher strength and stiffness. Additionally, M-N and M-C bonds contribute to the tensile strength of MXenes, reaching 1050 GPa and opening significant opportunities for their use as reinforcing materials in composite structures. While MXenes may demonstrate slightly lower performance compared to graphene, they offer excellent compatibility with polymeric phase to produce composites.

The thickness and number of layers also significantly influence the Young's modulus of MXenes. When comparing carbide and nitride MXenes, the latter exhibit higher maximum values. In both cases, a decrease in the number of layers correlates with an increase in the Young's modulus (Palledino & Baino, 2025). Others are;

- High metallic conductivity (up to ~10,000 S/cm for Ti_3C_2Tx films)
- Hydrophilicity and solution processability
- Surface functionalization capability
- Large surface area and tunable interlayer spacing
- Chemical stability
- Optical properties
- Electronics and physical properties

These characteristics enable MXenes to be integrated into stretchable electrodes, flexible supercapacitors, biosensors, pressure sensors, strain gauges, electromagnetic interference (EMI) shielding layers, and energy storage devices (Zhang, et al. (2022)

MXENE FOR FLEXIBLE ELCTRONICS

In the field of flexible electronics, MXenes are widely utilized as conductive films, electrodes, interconnects, and electromagnetic interference (EMI) shielding layers (Chen et al.,2025) Their compatibility with solution-based processing techniques—such as spray coating, inkjet printing, and vacuum-assisted filtration—supports scalable and cost-effective fabrication. Recent investigations have shown that MXene thin films maintain stable electrical performance under repeated bending and mechanical cycling, demonstrating their suitability for foldable and stretchable electronic circuits (Anasori, & Gogotsi, 2023).

.MXene-based strain and pressure sensors demonstrate high sensitivity, fast response time, and excellent mechanical durability due to their layered structure and conductive networks. For example, $Ti_3C_2T_x$ MXene films integrated with elastomeric substrates exhibit enhanced piezoresistive performance suitable for real-time physiological monitoring such as pulse detection and motion tracking (Li et al., 2022). The ability to form conductive percolation networks within flexible polymers significantly improves signal stability under repeated bending and stretching.

Another important development involves MXene-based flexible energy storage **devices**, including supercapacitors and micro-supercapacitors. Owing to their metallic conductivity and redox-active surface terminations, MXenes provide high volumetric capacitance and rapid ion transport. Flexible MXene films and textile-integrated electrodes have demonstrated excellent electrochemical performance while maintaining structural integrity under mechanical deformation (Shah et al., 2023). These properties make them suitable for powering next-generation wearable electronics.

communication modules, and power sources that allow them to collect, process, and transmit data in real time.

Recent studies also highlight progress in EMI shielding and conductive films. MXene thin films exhibit outstanding EMI shielding effectiveness due to their high conductivity and layered architecture, which enhances reflection and absorption of electromagnetic waves (Anasori & Gogotsi, 2023). Flexible MXene coatings applied to fabrics and polymers provide lightweight, bendable shielding materials for portable and wearable electronic systems.

Furthermore, advancements in device integration strategies, such as inkjet printing, spray coating, and 3D printing of MXene inks, have enabled scalable fabrication of flexible circuits and electronic components (Li et al., 2022). These processing techniques preserve electrical performance while allowing large-area and cost-effective manufacturing

Overall, recent advancements demonstrate that MXenes play a transformative role in flexible electronic technologies by combining high conductivity, mechanical adaptability, and surface tunability. Continued research in stability improvement, large-scale synthesis, and multifunctional integration is expected to further accelerate the commercialization of MXene-enabled flexible devices.

MXENE FOR SMART WEARING DEVICES

Wearable devices are electronic technologies that are designed to be worn on the body as accessories, clothing, or implanted items. They are equipped with sensors, processors, wireless

For wearable device applications, MXene-based sensors have exhibited remarkable sensitivity and reliability in monitoring physiological signals, including strain, pressure, pulse, respiration, and electrophysiological activities such as ECG and EMG. Flexible pressure and strain sensors fabricated from MXene composites present high gauge factors, rapid response times, low detection thresholds, and broad sensing ranges. More recent studies (2024–2025) report breathable and textile-integrated MXene sensors designed for long-term skin contact, improving comfort, biocompatibility, and signal stability in smart healthcare systems (Nishat et al.,2025)

In addition, MXenes play a crucial role in smart sensing technologies due to their large specific surface area, high electrical conductivity, and redox-active surface chemistry. These features enhance electron transfer efficiency in electrochemical biosensors and gas sensors, resulting in improved sensitivity and faster detection compared to conventional carbon-based materials. Advances between 2023 and 2025 have focused on improving selectivity and environmental stability through surface engineering, polymer hybridization, and encapsulation strategies aimed at reducing oxidation-related degradation.

Mxene and its challenges

Despite their promising characteristics, several technical challenges must be addressed before widespread commercialization can occur. MXenes are susceptible to oxidation in ambient environments, which compromises long-term device stability. $Ti_3C_2T_x$, the most studied MXene, undergoes degradation when exposed to oxygen and moisture, which significantly reduces conductivity and structural integrity (Anasori et al., 2017). Oxidation results in the formation of TiO_2, thereby degrading the material's performance in energy storage and electronic devices.

Most MXenes are synthesized using hydrofluoric acid (HF) or fluoride-containing etchants, which pose safety and environmental concerns (Naguib et al., 2011). The hazardous nature of these chemicals limits scalability and industrial production. Developing greener and safer etching strategies remains essential for large-scale commercialization Commercial adoption requires scalable, reproducible, and cost-effective production methods. Currently, uniform layer control and batch-to-batch consistency are difficult to maintain. Integration into industrial manufacturing

lines, especially for flexible electronics and EMI shielding materials, also requires mechanical stability and long-term durability (Anasori et al., 2017).

The lack of standardized characterization methods and regulatory guidelines for MXene-based materials slows industrial adoption. For example, variations in surface terminations significantly affect electrical and electrochemical performance, making reproducibility a challenge. Furthermore, achieving large-scale synthesis with controlled surface terminations, ensuring mechanical durability under cyclic strain, and optimizing integration with flexible substrates remain active areas of research. Current efforts emphasize antioxidant treatments, protective coatings, and advanced composite designs to enhance durability while preserving electrical functionality

Biomedicaly, although MXenes show promising antibacterial and photothermal properties, concerns remain regarding long-term cytotoxicity and in vivo safety. Rasool et al. (2016) demonstrated antibacterial activity of $Ti_3C_2T_x$, but further studies are required to assess its interaction with human tissues and immune responses. Surface chemistry plays a critical role in determining toxicity. Functional groups and oxidation states can influence reactive oxygen species (ROS) generation, which may cause cellular damage (Lin et al., 2022).The cost of MXene production and fabrication processes needs to be competitive with existing materials for widespread adoption (Maisha & Muhammed., 2023). Researchers must explore cost-effective synthesis methods and fabrication techniques. Assessing the environmental impact of MXene synthesis and disposal is crucial. Understanding potential environmental risks and developing sustainable practices is essential for the responsible use of MXenes in flexible and wearable electronics

Conclusion

MXenes have emerged as a highly promising class of two-dimensional materials for flexible electronics, wearable systems, and smart sensors, owing to their exceptional electrical conductivity, mechanical compliance, and rich surface chemistry. Since the first report of Ti3C2Tx, substantial advances have been achieved in materials synthesis, film fabrication, composite engineering, and device integration. However, despite impressive laboratory-scale demonstrations, the field remains at a transitional stage between proof-of-concept performance and technologically viable deployment.

A critical challenge lies in the intrinsic instability of MXenes under ambient and physiological conditions. Oxidation, surface degradation, and structural restacking significantly compromise long-term electrical performance and mechanical reliability—factors that are particularly crucial for wearable and biointegrated devices. Although encapsulation and antioxidant strategies have shown partial success, a mechanistic understanding of degradation pathways and standardized lifetime evaluation protocols are still lacking. Without addressing environmental stability and reproducibility, large-scale commercialization will remain constrained

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NOVEL THERMAL BARRIER COATINGS BASED ON HIGH-ENTROPY CERAMIC OXIDES

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Abstract

High entropy ceramic oxides (HECOs) are a new class of thermal barrier coatings (TBCs) designed to surpass conventional yttria-stabilized zirconia (YSZ) in aerospace and energy applications. By exploiting configurational entropy, HECOs stabilize single-phase structures that deliver improved thermal and mechanical performance. Recent work highlights advances in HECO design, deposition methods such as EB-PVD, plasma spraying, and additive manufacturing, and strategies for microstructural control. Studies shows HECOs possess ultra-low thermal conductivity, stability above 1400 °C, and strong resistance to oxidation and infiltration. Compared to traditional ceramics, they offer better fracture toughness, creep resistance, and bond coat compatibility. Their tunable thermal expansion coefficients reduce mismatch stresses, while sluggish cation diffusion enhances corrosion resistance. These properties make HECOs promising for jet engines, gas turbines, and hypersonic vehicles. Future directions include AI-guided design for rapid discovery, integration with environmental barrier coatings, and multi-scale modeling. Sustainable development—especially reducing rare earth use—will be vital for industrial adoption. Over the next decade, HECOs are expected to move from research to real-world deployment, redefining durability and efficiency in advanced propulsion and power systems.

Keywords: High entropy ceramic oxides, thermal barrier coatings, gas turbines, aerospace materials, plasma spraying, additive manufacturing

Introduction

Thermal barrier coatings (TBCs) are indispensable in modern high-temperature applications, particularly in aerospace propulsion and energy generation systems. Conventional TBCs, such as yttria-stabilized zirconia (YSZ), have enabled engines to operate at elevated temperatures by providing insulation against heat, oxidation, and corrosion. However, their performance is limited by phase instability, sintering, and susceptibility to thermal cycling degradation, which restricts efficiency gains in next-generation turbine technologies (Vakilifard et al., 2024). In response to these challenges, high entropy ceramic oxides (HECOs) have emerged as novel classes of materials for TBCs. HECOs are characterized by multiple principal cations distributed within a single crystalline lattice, stabilized by configurational entropy. This unique structural feature imparts exceptional phase stability, reduced thermal conductivity, and enhanced resistance to microstructural degradation under extreme thermal conditions (Liu et al., 2025)

. Unlike conventional ceramics, HECOs can maintain their integrity over prolonged service times, even under cyclic thermal loading, making them highly suitable for advanced turbine applications.

The introduction of HECO-based TBCs represents a paradigm shift in surface engineering. Their compositional flexibility allows tailoring of thermal expansion coefficients to minimize mismatch stresses between coating and substrate, thereby improving adhesion and durability (Vakilifard et al., 2024). Furthermore, rare-earth-based HECOs have demonstrated superior oxidation resistance and mechanical toughness, expanding their applicability beyond aerospace into automotive and industrial energy systems (Zhou et al., 2023). As global industries demand higher efficiency and sustainability, the development of HECO-based TBCs offers a pathway toward achieving these goals. By enabling higher operating temperatures and longer component lifetimes, these coatings not only enhance performance but also reduce maintenance costs and environmental impact. Thus, HECOs stand at the forefront of next-generation thermal barrier technologies, promising transformative advancements in high-temperature engineering.

Importance of Thermal Barrier Coatings (TBCs)

Thermal barrier coatings (TBCs) are advanced protective layers widely applied in high-temperature engineering systems, particularly gas turbines, aircraft engines, and industrial furnaces. Their primary function is to insulate metallic components from extreme thermal environments, thereby enhancing durability and efficiency. TBCs typically consist of ceramic topcoats, such as yttria-stabilized zirconia, which provide low thermal conductivity and high thermal shock resistance (Bogdan & Peter, 2024).

The importance of TBCs lies in their ability to extend the lifespan of critical components by reducing oxidation, corrosion, and thermal fatigue. For instance, in gas turbine blades, TBCs allow engines to operate at higher temperatures, improving fuel efficiency and reducing emissions (Thakare et al., 2021). This capability is vital for modern aerospace and energy industries, where performance demands continue to rise. Furthermore, TBCs contribute to cost savings by minimizing maintenance frequency and preventing catastrophic failures associated with thermal degradation (Bogdan & Peter, 2024).

Recent advancements in deposition techniques, such as electron beam physical vapor deposition and plasma spraying, have improved coating adhesion and microstructural stability. These innovations enhance the reliability of TBCs under cyclic thermal loading, a common challenge in turbine operation (Thakare et al., 2021). Beyond aerospace, TBCs are increasingly applied in automotive engines and industrial processing units, underscoring their versatility.

Limitations of Conventional Yttria-Stabilized Zirconia (YSZ) as Thermal Barriers

Yttria-stabilized zirconia (YSZ) has long been the benchmark material for thermal barrier coatings (TBCs) in gas turbines and aerospace engines due to its low thermal conductivity, high melting point, and resistance to thermal shock. Despite these advantages, YSZ exhibits several critical limitations that restrict its performance in next-generation high-temperature applications. One major limitation is its maximum operating temperature capability, which is generally restricted to around 1200 °C. Beyond this threshold, the metastable tetragonal phase ((t')) of YSZ tends to transform into the monoclinic phase, leading to volume changes, microcracking, and eventual coating failure (Vaßen et al., 2020). This phase instability significantly limits the efficiency improvements achievable in turbine engines, where higher combustion temperatures are desired.

Another challenge is sintering and microstructural degradation at elevated temperatures. Prolonged exposure to high heat causes grain growth and densification in YSZ, which increases thermal conductivity and reduces its insulating effectiveness (Eko, 2024). This degradation undermines the long-term reliability of the coating and necessitates frequent maintenance or replacement. YSZ also suffers from limited resistance to calcium–magnesium–alumino–silicate (CMAS) attack, a common issue in aerospace environments where molten deposits from ingested dust and sand infiltrate the coating. CMAS infiltration leads to chemical reactions that destabilize the YSZ structure, accelerating spallation and reducing service life (NASA, 2020).

Furthermore, thermal expansion mismatch between YSZ and metallic substrates can induce residual stresses during thermal cycling. These stresses contribute to delamination and cracking, particularly under rapid heating and cooling conditions (Vaßen et al., 2020).

Emergence of High Entropy Ceramic Oxides (HECOs) as Novel Thermal Barriers

Thermal barrier coatings (TBCs) are critical in protecting metallic components of gas turbines and aerospace engines from extreme thermal environments.

Conventional materials such as yttria-stabilized zirconia (YSZ) have been widely used due to their low thermal conductivity and high thermal shock resistance. However, limitations in phase stability, sintering resistance, and susceptibility to environmental degradation have prompted the search for advanced alternatives (Vakilifard et al., 2024).

High entropy ceramic oxides (HECOs) have emerged as a novel class of materials offering significant improvements over traditional TBCs. HECOs are defined by their multi-principal cation compositions, stabilized through configurational entropy. This entropy-driven stabilization imparts unique properties such as enhanced phase stability, reduced thermal conductivity, and superior resistance to microstructural degradation under cyclic thermal loading (Liu et al., 2025). These attributes make HECOs particularly suitable for next-generation turbine engines, where higher operating temperatures are essential for improved efficiency and reduced emissions

One of the key advantages of HECOs is their compositional flexibility, which allows tailoring of thermal expansion coefficients to minimize mismatch stresses between coating and substrate. This reduces the risk of delamination and extends service life (Vakilifard et al., 2024). Additionally, HECOs demonstrate improved resistance to calcium–magnesium–alumino–silicate (CMAS) infiltration, a major challenge in aerospace environments. Their ability to withstand chemical attack and maintain structural integrity under harsh conditions positions them as transformative materials for advanced thermal management systems (UTUPub, 2023).

Recent research has also highlighted the potential of rare-earth-based HECOs, which exhibit superior oxidation resistance and mechanical toughness. These properties expand their applicability beyond aerospace into automotive and industrial energy systems, underscoring their versatility (Liu et al., 2025). As global industries demand higher efficiency and sustainability, HECO-based TBCs provide a pathway toward achieving these goals by enabling higher operating temperatures, longer component lifetimes, and reduced maintenance costs.

The primary objective of this review is to critically examine the emergence of high entropy ceramic oxides (HECOs) as promising alternatives to conventional thermal barrier coatings (TBCs). Traditional materials, such as yttria-stabilized zirconia (YSZ), have served as the industry standard but face limitations in phase stability, sintering resistance, and environmental durability. This review aims to highlight how HECOs, with their unique entropy-driven stabilization, can overcome these challenges and enable next-generation high-temperature applications. Another key objective is to analyze the structural and functional advantages of HECOs, including their reduced thermal conductivity, enhanced oxidation resistance, and superior mechanical toughness. By exploring these properties, the review seeks to establish HECOs as viable candidates for aerospace, automotive, and industrial energy systems. Additionally, the review intends to evaluate recent research progress in HECO synthesis, deposition techniques, and performance testing. This includes examining rare-earth-based HECOs and their potential to resist calcium–magnesium–alumino–silicate (CMAS) infiltration, a critical issue in turbine environments. Ultimately, the review's objective is to provide a comprehensive understanding of HECO-based TBCs, identify current challenges, and outline future research directions that could accelerate their adoption in sustainable, high-efficiency energy and transportation technologies.

Fundamentals of Thermal Barrier Coatings

Function and Design Principles of Thermal Barrier Coatings

Thermal barrier coatings (TBCs) are advanced protective layers applied to metallic components in high-temperature environments such as gas turbines, jet engines, and industrial furnaces. Their primary function is to insulate underlying substrates from extreme heat, thereby enhancing durability, efficiency, and service life. By reducing the thermal load on metallic alloys, TBCs enable engines to operate at higher combustion temperatures, which improve fuel efficiency and reduce emissions (Bogdan & Peter, 2024). The functional role of TBCs extends beyond thermal insulation. They also provide resistance to oxidation, corrosion, and thermal fatigue, which are common degradation mechanisms in turbine blades and combustors. Additionally, TBCs mitigate thermal expansion mismatch between ceramic coatings and metallic substrates, reducing the risk of delamination during cyclic heating and cooling (Mondal et al., 2021).

The design principles of TBCs are guided by several critical factors:

- Material selection: Ceramic oxides such as yttria-stabilized zirconia are commonly used due to their low thermal conductivity and high melting point. Emerging materials, including high entropy oxides, are being explored for improved phase stability.

- Microstructural design: Porosity and columnar grain structures are engineered to reduce thermal conductivity and enhance strain tolerance under thermal cycling.
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- Deposition techniques: Methods such as plasma spraying and electron beam physical vapor deposition are employed to achieve desired microstructures and coating adhesion.
- Layer architecture: TBCs typically consist of a metallic bond coat for oxidation resistance and a ceramic topcoat for thermal insulation. Advanced designs may incorporate multilayered or graded structures to optimize performance (Bogdan & Peter, 2024).

Conventional Thermal Barrier Coating Materials and Their Drawbacks

Thermal barrier coatings (TBCs) are essential in protecting metallic components of gas turbines, aircraft engines, and industrial systems from extreme thermal environments. Conventional TBC materials, particularly yttria-stabilized zirconia (YSZ), have dominated the field due to their low thermal conductivity, high melting point, and good thermal shock resistance. However, despite their widespread use, conventional TBCs exhibit several limitations that restrict their long-term performance in next-generation high-temperature applications.

Yttria-Stabilized Zirconia (YSZ):

YSZ remains the most widely used TBC material because of its favorable thermal insulation properties. Yet, its maximum operating temperature is limited to approximately 1200 °C. Beyond this threshold, YSZ undergoes phase instability, transforming from the metastable tetragonal phase to the monoclinic phase, which results in volume changes, microcracking, and eventual coating failure (Bogdan & Peter, 2024). Additionally, YSZ suffers from sintering at elevated temperatures, leading to grain coarsening and densification. This increases thermal conductivity over time, reducing its effectiveness as an insulator (Raza et al., 2022).

Alumina-Based Coatings:

Alumina has been explored as a TBC material due to its oxidation resistance. However, its relatively high thermal conductivity compared to YSZ limits its efficiency. Moreover, alumina coatings are prone to spallation under cyclic thermal loading, reducing their reliability in turbine applications (Bogdan & Peter, 2024).

2.5 Mullite and Other Silicate-Based Coatings:

Mullite and silicate-based coatings offer good resistance to corrosive environments but lack the thermal stability required for prolonged exposure to extreme temperatures. Their brittleness and poor strain tolerance under thermal cycling further restrict their use in advanced turbine systems (Raza et al., 2022).

2.5 Common Drawbacks Across Conventional Materials:

- Phase instability under high temperatures.
- Sintering and microstructural degradation, which increase thermal conductivity.
- Susceptibility to CMAS (calcium–magnesium–alumino–silicate) infiltration, leading to chemical degradation in aerospace environmen

- Thermal expansion mismatch with metallic substrates, causing delamination and cracking during cyclic heating and cooling (Bogdan & Peter, 2024).

Conventional TBC materials such as YSZ, alumina, and mullite have provided significant advancements in thermal management, their inherent drawbacks limit their application in next-generation turbine engines. These challenges have driven research toward novel materials, such as high entropy ceramic oxides (HECOs), which promise improved phase stability, reduced sintering, and enhanced resistance to environmental degradation.

Thermal Barrier Coating Desired Properties: Low Thermal Conductivity, Phase
Stability, and Oxidation Resistance

Thermal barrier coatings (TBCs) are engineered to protect metallic components in high-temperature environments such as gas turbines and aerospace engines. Their effectiveness depends on achieving a balance of critical properties, including low thermal conductivity, phase stability, and oxidation resistance. These properties collectively determine the durability, efficiency, and reliability of the coating system.

Low Thermal Conductivity

The primary function of TBCs is to insulate metallic substrates from extreme heat. Materials with low thermal conductivity reduce heat transfer, allowing engines to High entropy materials (HEMs) represent a novel class of advanced materials characterized by their unique compositional and structural design. Unlike conventional alloys or ceramics, which are typically based operate at higher combustion temperatures without damaging underlying alloys. Advanced ceramic oxides, such as yttria-stabilized zirconia (YSZ), have been widely used due to their inherently low conductivity. Recent research emphasizes defect engineering and multi-component oxides to further suppress thermal transport, thereby enhancing efficiency in turbine applications (Zeraati et al., 2024).

Phase Stability

Phase stability is essential for maintaining structural integrity under prolonged thermal exposure. Conventional YSZ suffers from phase transformation at temperatures above 1200 °C, leading to microcracking and spallation. Novel approaches, including multi-component defect clustering and high entropy oxides, have demonstrated improved phase stability, enabling coatings to withstand higher operating temperatures without degradation (Zhu & Miller, 2024).

Oxidation Resistance

Oxidation resistance ensures that coatings can withstand corrosive environments and prevent oxygen diffusion into metallic substrates. Bond coats, often composed of MCrAlY alloys, provide a protective layer against oxidation. However, advanced ceramic topcoats with tailored compositions are increasingly being designed to resist both oxidation and calcium–magnesium–alumino–silicate (CMAS) infiltration, which is a major cause of coating failure in aerospace engines (Zhu & Miller, 2024).

High-Entropy Ceramic Oxides (HECOs)

Concept of High Entropy Materials

on one or two principal elements, HEMs are composed of multiple principal elements—often five or more—in near-equimolar ratios. This compositional complexity leads to high configurational entropy, which stabilizes single-phase solid solutions and imparts remarkable properties (Ren et al., 2025).

The concept of high entropy materials was first introduced through high entropy alloys (HEAs), which demonstrated exceptional mechanical strength, corrosion resistance, and thermal stability. This principle has since been extended to ceramics, oxides, and composites, giving rise to high entropy ceramic oxides (HECOs) and other multifunctional materials (Ma et al., 2021). The entropy-driven stabilization mechanism reduces the tendency for phase separation, enabling materials to maintain structural integrity under extreme conditions.

HEMs are particularly significant because they offer tailorable chemical compositions and tunable functional properties. By varying the constituent elements, researchers can design materials with specific thermal, electrical, or mechanical characteristics. For instance, HECOs exhibit low thermal conductivity and high phase stability, making them promising candidates for thermal barrier coatings in aerospace and energy systems (Ren et al., 2025).

Furthermore, HEMs demonstrate enhanced resistance to oxidation, wear, and chemical attack, which expands their applicability in renewable energy technologies, catalysis, and high-temperature structural applications (Ma et al., 2021). Their multifunctionality positions them as transformative materials for sustainable engineering solutions.

Configurational Entropy and Stabilization Mechanisms of High Entropy Materials (HEMs)

High entropy materials (HEMs) represent a paradigm shift in materials science, distinguished by their multi-principal element compositions. Unlike conventional alloys or ceramics, which are based on one or two dominant elements, HEMs typically incorporate five or more elements in near-equimolar ratios. This compositional complexity generates high configurational entropy, which plays a central role in stabilizing single-phase solid solutions and imparting unique functional properties (Ye, Li, & Gu, 2022).

Configurational Entropy in HEMs

Configurational entropy arises from the random distribution of multiple cations or atoms within a lattice. The entropy contribution increases with the number of constituent elements, favoring the formation of disordered solid solutions over ordered intermetallic compounds. This entropy-driven stabilization reduces the Gibbs free energy of the system, thereby suppressing phase separation and enhancing structural uniformity (Gupta, 2022). In ceramic systems, such as high entropy oxides, configurational entropy enables the coexistence of diverse cations in a single lattice, resulting in improved phase stability under extreme thermal conditions (Ye et al., 2022).

Stabilization Mechanisms

The stabilization of HEMs is governed by the interplay of entropy and enthalpy. While enthalpic contributions from atomic size mismatch and lattice distortion can destabilize structures, the high configurational entropy offsets these effects, promoting solid-solution formation. Predictive parameters such as atomic size difference ((\delta)), mixing enthalpy (Delta H_{mix}), and valence electron concentration (VEC) are often used to evaluate stability (Gupta, 2022). In oxides, entropy-driven stabilization also influences thermal transport, reducing thermal conductivity by scattering phonons across multiple cation sites (arXiv, 2023).

Implications Material Design

The entropy-stabilized nature of HEMs allows for tunable properties, including enhanced mechanical strength, corrosion resistance, and thermal stability. In high entropy ceramic oxides, configurational entropy contributes to superior phase stability and oxidation resistance, making them promising candidates for thermal barrier coatings in aerospace and energy systems (Ye et al., 2022). Furthermore, entropy-driven stabilization mechanisms open pathways for designing multifunctional materials with tailored properties for catalysis, energy storage, and structural applications.

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Synthesis Routes of High Entropy Materials (HEMs): Solid-State, Sol-Gel, and Plasma Spraying

High entropy materials (HEMs), including high entropy alloys and high entropy ceramic oxides, have attracted significant attention due to their unique entropy-driven stabilization and multifunctional properties. The synthesis of HEMs is critical to achieving desired microstructures and performance. Among the most studied synthesis routes are solid-state reactions, sol-gel methods, and plasma spraying, each offering distinct advantages and limitations

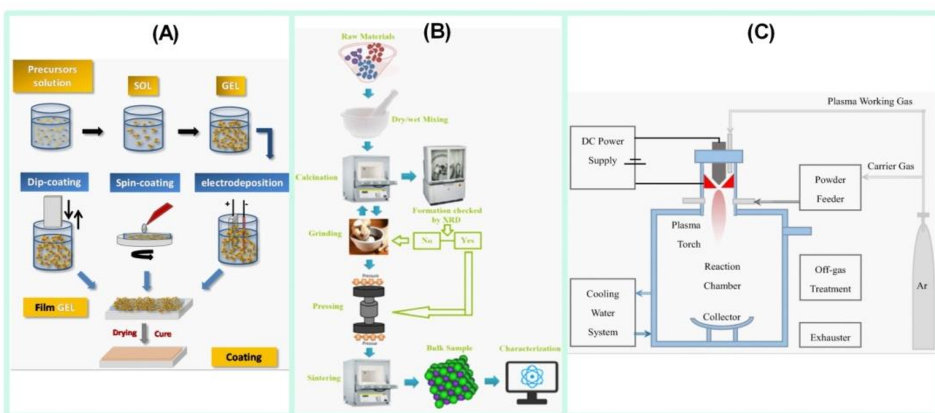

Fig. 1: Synthesis routes are solid-state reactions, sol-gel methods, and plasma spraying of ceramics (Mandracci and Rivolo, 2023: Figueira, Fontinha, Silva and Pereira, 2016).

Sol-Gel Method

The sol-gel route offers superior control over composition and microstructure. In this method, metal alkoxides or nitrates are hydrolyzed to form a colloidal sol, which transitions into a gel and is subsequently calcined. Sol-gel synthesis enables uniform mixing at the molecular level, resulting in highly homogeneous HEMs with fine particle sizes and enhanced surface area. This approach has been particularly effective in producing high entropy spinel and fluorite oxides for catalytic and electrochemical applications (Petrovičová et al., 2022). However, sol-gel synthesis can be more complex and costly compared to solid-state methods.

Plasma Spraying

Plasma spraying is a versatile technique for fabricating HEM coatings, especially for thermal barrier applications. In this process, powdered precursors are injected into a plasma jet, melted, and deposited onto substrates to form dense coatings. Plasma spraying allows for rapid deposition, scalability, and the ability to tailor coating thickness and microstructure. High entropy oxides synthesized via plasma spraying have demonstrated excellent adhesion, oxidation resistance, and thermal stability, making them promising candidates for next-generation turbine engines (Asim et al., 2022). The main drawback lies in the need for precise process control to avoid compositional segregation.

Comparative Insights

- Solid-state synthesis: cost-effective, but limited by long processing times and coarse microstructures.
- Sol-gel method: produces highly homogeneous, fine-grained HEMs, but involves complex chemistry.
- Plasma spraying: ideal for coatings with tailored architectures, though process optimization is critical.

Structural Diversity of High Entropy Materials (HEMs): Fluorite, Perovskite, and Spinel

High entropy materials (HEMs), particularly high entropy oxides (HEOs), exhibit remarkable structural diversity due to their multi-principal element compositions. Unlike conventional ceramics, which are typically based on one or two dominant cations, HEMs incorporate multiple cations in near-equimolar ratios. This compositional complexity allows stabilization of diverse crystal structures such as fluorite, perovskite, and spinel, each offering unique functional properties (Kandage & Marszewski, 2024)

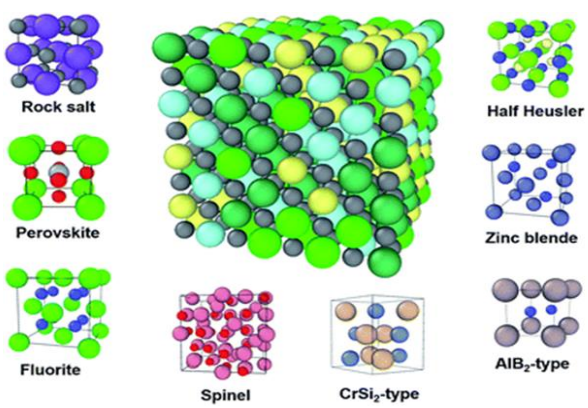

Fig. 2: Structural diversity of the HEC family. The central image shows a supercell of a HEC rock salt structure (Zhang and Reece, 2019).

Fluorite Structures: Fluorite-type HEOs are among the most studied due to their low thermal conductivity and high ionic conductivity. The random distribution of multiple cations within the fluorite lattice enhances phonon scattering, reducing thermal transport and making them ideal candidates for thermal barrier coatings (Barber et al., 2025). Additionally, fluorite HEOs exhibit excellent phase stability under high temperatures, which is critical for aerospace and energy applications.

Perovskite Structures: Perovskite-type HEMs are notable for their tunable electronic and catalytic properties. The entropy-driven stabilization allows multiple cations to coexist in both A and B sites of the perovskite lattice, enabling tailored functionalities such as enhanced oxygen mobility and catalytic activity (Kandage & Marszewski, 2024). These properties make high entropy perovskites promising for solid oxide fuel cells, catalysis, and energy conversion technologies.

Spinel Structures: Spinel-type HEMs exhibit excellent mechanical strength and chemical stability. Their structural flexibility allows incorporation of diverse cations in tetrahedral and octahedral sites, resulting in enhanced oxidation resistance and electrochemical performance (Barber et al., 2025). High entropy spinels have been investigated for applications in batteries, magnetic devices, and protective coatings, where durability under harsh environments is essential.

Comparative Insights

- Fluorite HEMs: Best suited for thermal barrier coatings due to low thermal conductivity.
- Perovskite HEMs: Ideal for catalytic and energy applications owing to oxygen mobility.
- Spinel HEMs: Strong candidates for electrochemical and protective applications due to mechanical robustness.

Novel HECOs for TBCs

The development of high entropy ceramic oxides (HECOs) has opened new pathways for advanced thermal barrier coatings (TBCs). Among these, rare earth zirconates (REZs) have attracted significant attention due to their unique thermophysical properties and entropy-driven stabilization mechanisms. Conventional yttria-stabilized zirconia (YSZ) coatings, while widely used, face limitations such as phase instability and susceptibility to sintering at temperatures above 1200 °C. Rare earth zirconates, particularly in high entropy configurations, offer promising solutions to overcome these drawbacks (Liu et al., 2022).

Low Thermal Conductivity and Phase Stability

High entropy rare earth zirconates, such as $((La_{0.2}Nd_{0.2}Sm_{0.2}Gd_{0.2}Yb_{0.2})_2Zr_2O_7)$, exhibit significantly lower thermal conductivity compared to conventional YSZ. This reduction is attributed to phonon scattering caused by the random distribution of multiple rare earth cations within the lattice. The entropy-driven stabilization also enhances phase stability, preventing deleterious phase transformations under prolonged thermal cycling (Liu et al., 2022).

Oxidation and CMAS Resistance

Rare earth zirconates demonstrate superior resistance to oxidation and calcium–magnesium–alumino–silicate (CMAS) infiltration, a critical issue in aerospace engines. Their robust chemical stability ensures longer service life and reduced maintenance costs, making them highly suitable for turbine blades and combustor liners (MDPI, 2023).

Mechanical and Microstructural Advantages

HECO-based zirconates also exhibit improved mechanical toughness and microstructural stability. Tailored pore structures in porous high entropy zirconates enhance strain tolerance and thermal shock resistance, further extending their applicability in high-performance environments (MDPI, 2023).

The integration of rare earth zirconates into HECO frameworks represents a paradigm shift in TBC design. Their combination of low thermal conductivity, high phase stability, and superior environmental resistance positions them as strong candidates for next-generation aerospace and energy systems. Continued research into synthesis methods, such as solid-state reactions and plasma spraying, will be crucial for optimizing their performance and scalability.

Novel High Entropy Ceramic Oxides (HECOs) for Thermal Barrier Coatings: Multi-Component Oxides (e.g., (La, Nd, Sm, Gd, Y)$_2$Zr$_2$O$_7$)

High entropy ceramic oxides (HECOs) have emerged as transformative materials for thermal barrier coatings (TBCs), offering superior performance compared to conventional yttria-stabilized zirconia (YSZ). Among the most promising HECOs are multi-component rare earth zirconates, such as (La, Nd, Sm, Gd, Y)$_2$Zr$_2$O$_7$. These compositions leverage entropy-driven stabilization to achieve unique thermophysical properties that address the limitations of traditional TBCs (Liu et al., 2022).

Low Thermal Conductivity

Multi-component zirconates exhibit significantly lower thermal conductivity than YSZ. The random distribution of rare earth cations within the pyrochlore lattice enhances phonon scattering, thereby suppressing heat transport. This property is crucial for insulating turbine blades and combustor components, enabling higher operating temperatures and improved fuel efficiency (Zhou et al., 2023).

Phase Stability

Entropy stabilization ensures that multi-component zirconates maintain their structural integrity under extreme thermal cycling. Unlike YSZ, which undergoes deleterious phase transformations above 1200 °C, HECO zirconates remain stable, reducing risks of microcracking and spallation. This stability extends the service life of coatings in aerospace and energy systems (Vakilifard et al., 2024).

Oxidation CMAS Resistance

A major advantage of HECO zirconates is their superior resistance to oxidation and calcium–magnesium–alumino–silicate (CMAS) infiltration. CMAS attack, common in turbine environments due to ingested dust and sand, destabilizes conventional coatings. Multi-component zirconates resist such infiltration, maintaining protective performance even in aggressive conditions (Zhou et al., 2023).

Mechanical and Microstructural Properties

The incorporation of multiple rare earth cations also improves mechanical toughness and strain tolerance. Tailored porosity in plasma-sprayed HECO zirconates enhances thermal shock resistance, while entropy-driven lattice distortion contributes to superior mechanical stability under cyclic loading (Liu et al., 2022).

The development of multi-component zirconates such as ((La, Nd, Sm, Gd, Y)$_2$Zr$_2$O$_7$) represents a paradigm shift in TBC design. Their combination of low thermal conductivity, high phase stability, and environmental resistance positions them as strong candidates for next-generation turbine engines. Continued research into synthesis methods—including solid-state reactions, sol-gel processing, and plasma spraying—will be essential to optimize performance and scalability (Vakilifard et al., 2024).

Multi-component HECO zirconates exemplify the potential of entropy-stabilized ceramics in thermal barrier applications.

Their unique properties address the critical shortcomings of conventional materials, paving the way for more efficient, durable, and sustainable high-temperature technologies.

High Entropy Ceramic Oxides for Thermal Barrier Coatings: Perovskites and Pyrochlores

Thermal barrier coatings (TBCs) are critical in modern gas turbine engines, enabling higher operating temperatures and improved fuel efficiency. Conventional materials such as yttria-stabilized zirconia (YSZ) have been widely used; however, their limitations in phase stability above 1200 °C and vulnerability to calcium–magnesium–alumino–silicate (CMAS) infiltration have spurred interest in novel materials (Li et al., 2019). High entropy ceramic oxides (HECOs), particularly those with perovskite and pyrochlore structures, have emerged as promising candidates due to their unique stabilization mechanisms and tunable properties

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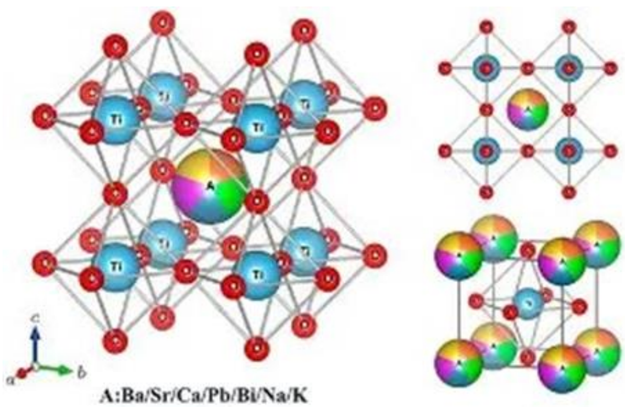

Fig. 3: Crystal structure of HEPOs with multiple elements at A-site.
The red sphere represents oxygen ion, the blue sphere represents titanium cation at B-site, andthe colored ball represents the multi-component cations at A-site (Zhou, Li, Liu and Zhang, 2023).

High entropy ceramics are defined by the incorporation of five or more cations in near-equimolar ratios, which generates high configurational entropy. This entropy stabilizes single-phase structures despite chemical complexity, leading to enhanced phase stability and reduced thermal conductivity (Wang et al., 2023). In perovskite-type HECOs, the A- and B-site cations can be varied extensively, allowing for lattice distortion and phonon scattering. These effects suppress thermal conductivity, a desirable property for TBCs, while maintaining structural integrity under extreme thermal cycling (Technološki fakultet Novi Sad, 2021).

High entropy pyrochlores, typically derived from rare-earth zirconates, have demonstrated particularly low thermal conductivity values. Li et al. (2019) synthesized pyrochlore-type HECOs using equimolar ratios of rare-earth oxides (La_2O_3, Nd_2O_3, Sm_2O_3, Eu_2O_3, Gd_2O_3, and Y_2O_3) combined with ZrO_2. The resulting materials exhibited significant phonon scattering due to mass and strain field fluctuations, leading to thermal conductivities lower than conventional pyrochlores. Moreover, the sluggish diffusion inherent in high entropy systems enhances resistance to CMAS infiltration, a major degradation mechanism in turbine environments

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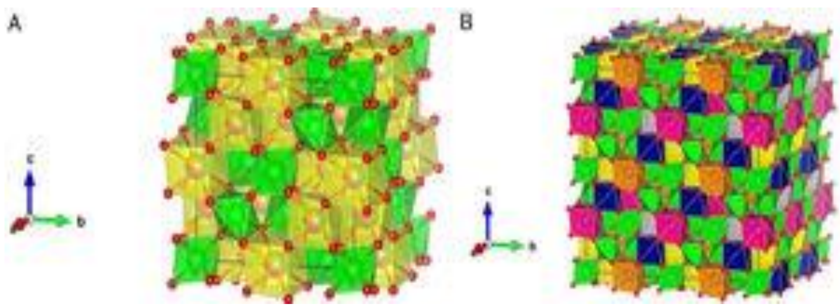

Fig. 4: (a) XRD Ordered pyrochlore structure obtained from the recorded (b) model of ordered pyrochlore structure generated using the 2×2×2 supercell. Lanthanum atoms/polyhedra in yellow color, yttrium in blue, gadolinium in gray, samarium in purple, neodymium in orange, zirconium in green, and oxygen atoms in red color (Banerjee, Parayil, Gupta, Modak, Mohapatra, 2024).

Computational studies further support the potential of high entropy pyrochlores. Wang et al. (2023) employed deep-learning potentials to predict thermophysical properties, highlighting their superior phase stability and mechanical robustness compared to conventional ceramics. These findings suggest that HECOs can withstand prolonged exposure to high temperatures without undergoing deleterious phase transformations, a critical requirement for next-generation TBCs.

Perovskite HECOs also offer unique advantages. Their flexible crystal chemistry allows incorporation of multiple cations, which enhances defect engineering and ionic conductivity. This tunability can be exploited to design coatings with tailored thermal and mechanical properties. Furthermore, the inherent disorder in high entropy perovskites contributes to reduced thermal conductivity, making them competitive with pyrochlore-based HECOs (Technološki fakultet Novi Sad, 2021).

Despite these advantages, challenges remain. Processing HECOs into coatings via plasma spraying or electron beam physical vapor deposition requires careful control of stoichiometry and phase purity. Additionally, long-term cyclic performance and compatibility with bond coats must be validated before industrial adoption. Nevertheless, the combination of low thermal conductivity, high phase stability, and CMAS resistance positions high entropy perovskites and pyrochlores as strong contenders for next-generation TBCs. HECOs represent a transformative approach to thermal barrier design. By leveraging configurational entropy, perovskite and pyrochlore HECOs achieve properties unattainable in conventional ceramics. Continued research into processing, performance evaluation, and computational modeling will be essential to realize their full potential in aerospace and energy applications.

Tailoring Composition of High Entropy Ceramic Oxides for Thermal Barrier Coatings

Thermal barrier coatings (TBCs) are essential in advanced gas turbine engines, enabling higher operating temperatures and improved efficiency. Conventional yttria-stabilized zirconia (YSZ) has been widely used, but its limitations in phase stability above 1200 °C and susceptibility to calcium–magnesium–alumino–silicate (CMAS) infiltration have motivated the search for novel alternatives. High entropy -equimolar ratios, offer a promising pathway to overcome these challenges by tailoring composition to optimize performance (Vakilifard et al., 2024).

The tailoring of HECO composition relies on configurational entropy, which stabilizes single-phase structures despite chemical complexity. By carefully selecting cations with varying ionic radii and valence states, researchers can engineer lattice distortions that enhance phonon scattering, thereby reducing thermal conductivity—a critical property for TBCs (Liu et al., 2025). For example, rare-earth elements such as La, Nd, and Gd incorporated into zirconate-based HECOs have demonstrated lower thermal conductivity compared to conventional pyrochlores, while simultaneously improving resistance to CMAS attack due to sluggish cation diffusion (Liu et al., 2025).

Tailoring composition also allows optimization of phase stability. Zr-Y-Yb-Ta-Nb-O systems, designed using the high entropy concept, exhibit stabilized Computational modeling has further accelerated the design of tailored HECO compositions. Machine learning and deep-learning potentials have been employed to predict thermophysical properties across vast compositional spaces, guiding experimental synthesis toward optimal

ceramic oxides (HECOs), which incorporate multiple cations in near

tetragonal phases that resist transformation under high-temperature cycling (Zhou et al., 2023). This compositional flexibility enables coatings to maintain structural integrity beyond the operational limits of YSZ. Moreover, the inclusion of multiple cations with different oxidation states can improve resistance to oxygen diffusion, thereby enhancing oxidation and corrosion resistance in turbine environments (Vakilifard et al., 2024).

Another key aspect of compositional tailoring is balancing mechanical properties with thermal performance. While reducing thermal conductivity is essential, coatings must also exhibit adequate toughness to resist spallation during thermal cycling. By adjusting the ratio of heavy cations (e.g., Ta, Nb) to lighter rare-earth elements, researchers can fine-tune elastic modulus and fracture toughness. This balance ensures that HECO-based coatings not only insulate effectively but also survive mechanical stresses encountered in service (Liu et al., 2025).

candidates (Vakilifard et al., 2024). These approaches reduce trial-and-error experimentation and highlight compositions with superior thermal and mechanical performance. Figure 5, shows schematics of machine learning guided synthesis and high through put screening

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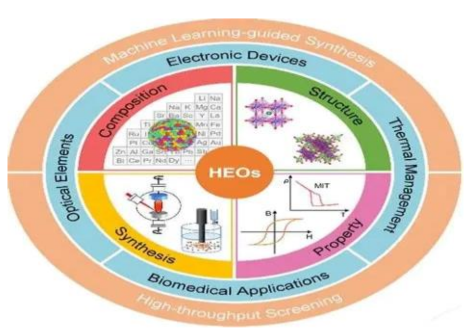

Fig. 5: Machine learning guided synthesis and high through put screening: synthesis, composition, structure and properties (Vakilifard et al., 2024).

Despite these advances, challenges remain in translating tailored HECO compositions into industrial coatings. Maintaining stoichiometry during deposition processes such as plasma spraying or electron beam physical vapor deposition is complex, and ensuring compatibility with bond coats requires further study. Nonetheless, tailoring composition offers a powerful strategy to unlock the full potential of HECOs for next-generation TBCs.

In summary, tailoring the composition of HECOs enables fine control over thermal conductivity, phase stability, CMAS resistance, and mechanical robustness. By leveraging configurational entropy and compositional flexibility, researchers are developing coatings that surpass the limitations of conventional ceramics. Continued integration of computational design and experimental validation will be essential to realize the industrial adoption of HECO-based TBCs

.**Table 1:** Comparative Analysis of Tailored HECO Compositions

Aspect	**Zr-based HECOs (e.g., Zr-Y-Yb-Ta-Nb-O)**	**Rare-earth-based HECOs (e.g., La-Nd-Sm-Gd-Y-Zr-O pyrochlores)**
Thermal Conductivity	Moderate (~1.5–2.0 W/m·K). Lower than YSZ due to lattice distortion and phonon scattering.	Very low (~1.0–1.3 W/m·K). Strong phonon scattering from mass/strain field fluctuations.
Phase Stability	Stabilized tetragonal phases; resistant to transformation under thermal cycling up to ~1400 °C (Zhou et al., 2023).	Excellent stability at >1400 °C; entropy stabilizes single-phase pyrochlore structures (Liu et al., 2025).
CMAS Resistance	Improved compared to YSZ, but less effective than rare-earth HECOs; infiltration slowed by sluggish cation diffusion.	Superior resistance; rare-earth cations hinder CMAS penetration and reaction, offering longer coating lifetimes (Vakilifard et al., 2024).
Pros	• Balanced mechanical toughness and thermal insulation. • Easier integration with existing bond coats. • More cost-effective than rare-earth systems.	• Ultra-low thermal conductivity. • Exceptional CMAS resistance. • Long-term stability at extreme temperatures.
Cons	• CMAS resistance moderate compared to rare-earth HECOs. • Thermal conductivity not as low as pyrochlores.	• Higher raw material costs (rare-earth oxides). • Potential supply chain limitations. • Processing complexity due to multiple rare-earth cations.
Cost Implications	Generally lower cost; Zr and Y are more abundant and cheaper than rare-earth elements.	Higher cost due to reliance on rare-earth oxides; economic feasibility depends on supply stability.
Processing Challenges	• Maintaining stoichiometry during plasma spraying. • Ensuring tetragonal phase retention during deposition.	• Achieving uniform distribution of multiple rare-earth cations. • Avoiding phase segregation during high-

Aspect	Zr-based HECOs (e.g., Zr-Y-Yb-Ta-Nb-O)	Rare-earth-based HECOs (e.g., La-Nd-Sm-Gd-Y-Zr-O pyrochlores)
		temperature processing.
Industrial Outlook	Attractive for near-term adoption due to cost-effectiveness and balanced performance.	Strong candidate for next-generation turbines where extreme CMAS resistance and ultra-low conductivity are critical.

Zr-based HECOs provide a cost-effective balance between thermal insulation and mechanical toughness. Their stabilized tetragonal phases make them resilient under thermal cycling, but their CMAS resistance remains moderate compared to rare-earth systems (Zhou et al., 2023). These compositions are attractive for near-term industrial adoption, particularly in applications where cost and mechanical reliability are prioritized.

Rare-earth-based HECOs, by contrast, deliver superior thermal and chemical performance, with ultra-low thermal conductivity and excellent CMAS resistance (Liu et al., 2025). However, their reliance on rare-earth oxides introduces economic and supply chain challenges, and processing complexity increases due to the need for uniform cation distribution (Vakilifard et al., 2024). These coatings are best suited for high-demand aerospace applications, where performance outweighs cost considerations.

Processing and Deposition Techniques

Thermal barrier coatings (TBCs) are critical in modern gas turbine engines, enabling higher operating temperatures and improved efficiency. Conventional yttria-stabilized zirconia (YSZ) has long been the benchmark material, but its limitations in phase stability and susceptibility to calcium–magnesium–alumino–silicate (CMAS) infiltration have motivated the exploration of high entropy ceramic oxides (HECOs). To fully exploit the potential of HECOs, advanced deposition techniques such as electron beam physical vapor deposition (EB-PVD), plasma spraying, and additive manufacturing are being investigated, with microstructural control playing a central role in performance optimization.

EB-PVD Deposition of HECOs

EB-PVD is a high-vacuum process in which a focused electron beam evaporates ceramic targets, depositing material onto substrates to form columnar microstructures. These columnar architectures provide strain tolerance, adhesion, and resistance to spallation under thermal cycling (Kulkarni et al., 2003). When applied to HECOs, EB-PVD enables retention of complex multi-cation compositions, producing coatings with ultra-low thermal conductivity and enhanced phase stability compared to YSZ (Dudnik et al., 2021). The intercolumnar porosity characteristic of EB-PVD coatings further improves stress relief, accommodating thermal expansion mismatches between coating and substrate.

Plasma Spraying Approaches

Plasma spraying, particularly atmospheric plasma spraying (APS) and suspension plasma spraying (SPS), remains one of the most widely used TBC deposition methods. APS produces lamellar microstructures with relatively high porosity, while SPS can generate columnar-like structures similar to EB-PVD but at lower cost (Mauer & Vaßen, 2015). For HECOs, plasma spraying offers flexibility in processing complex compositions, though challenges include maintaining stoichiometry and avoiding phase segregation during rapid solidification. Plasma spray–physical vapor deposition (PS-PVD) has also emerged as a hybrid technique capable of producing EB-PVD-like columnar structures, bridging the gap between cost and performance (Mauer & Vaßen, 2015).

Additive Manufacturing Approaches
Additive manufacturing (AM) techniques, such as laser-directed energy deposition and inkjet-based ceramic printing, are increasingly explored for HECO-based coatings. AM allows precise control over composition and microstructure, enabling gradient coatings and tailored architectures. For HECOs, AM provides opportunities to design coatings with spatially varying compositions, optimizing thermal conductivity and mechanical toughness simultaneously. However, challenges include achieving dense, defect-free coatings and scaling processes for industrial turbine components (Vakilifard et al., 2024).

Microstructural Control
Microstructural control is central to the performance of HECO-based TBCs. EB-PVD produces columnar structures with intercolumnar porosity, enhancing strain tolerance and thermal cycling resistance (Kulkarni et al., 2003). Plasma spraying generates splat-based lamellar structures, where porosity and crack networks influence thermal conductivity and toughness. Additive manufacturing offers unprecedented control, allowing design of hierarchical microstructures that combine low thermal conductivity with mechanical robustness. For HECOs, microstructural tailoring is particularly important because configurational entropy stabilizes single-phase structures, but deposition processes must preserve uniform cation distribution to maintain entropy-driven benefits (Dudnik et al., 2021).

Comparative Outlook
EB-PVD remains the gold standard for producing high-performance columnar coatings, though its cost and equipment requirements limit widespread adoption. Plasma spraying offers scalability and cost-effectiveness, with SPS and PS-PVD providing pathways to EB-PVD-like structures. Additive manufacturing represents a frontier approach, enabling compositional and microstructural tailoring beyond conventional methods. Ultimately, the choice of deposition technique depends on balancing performance, cost, and scalability, with microstructural control being the decisive factor in harnessing the full potential of HECOs for next-generation TBCs.

Thermal and Mechanical Properties
High entropy ceramic oxides (HECOs) have emerged as promising candidates for next-generation thermal barrier coatings (TBCs) due to their unique combination of thermal and mechanical properties. By incorporating multiple cations in near-equimolar ratios, HECOs achieve high configurational entropy, which stabilizes single-phase structures and enhances performance under extreme turbine operating conditions (Vakilifard et al., 2024).

Thermal Conductivity Reduction

A key requirement for TBCs is low thermal conductivity to insulate metallic substrates from high combustion temperatures. HECOs exhibit significantly reduced thermal conductivity compared to conventional yttria-stabilized zirconia (YSZ). This reduction arises from lattice distortion and phonon scattering caused by mass and strain field fluctuations among multiple cations (Aronkytö, 2025). For example, rare-earth zirconate-based HECOs demonstrate thermal conductivities as low as 1.0–1.3 W/m·K, outperforming YSZ and conventional pyrochlores. Such ultra-low conductivity enables higher turbine inlet temperatures and improved efficiency.

Phase Stability at High Temperatures

Phase stability is critical for coating longevity. YSZ suffers from destabilization above 1200 °C, whereas HECOs maintain stable single-phase structures beyond 1400 °C due to entropy-driven stabilization (Vakilifard et al., 2024). Studies show that Zr-Y-Yb-Ta-Nb-O HECOs retain tetragonal phases under prolonged thermal cycling, resisting deleterious transformations that typically lead to coating failure (Aronkytö, 2025). This stability ensures reliable performance in advanced turbine environments.

Thermal Expansion Coefficient Matching

Matching the thermal expansion coefficient (TEC) of the coating with that of the metallic substrate is essential to minimize thermal stresses. HECOs offer tunable TECs by adjusting cation composition. For instance, incorporating rare-earth elements such as La, Nd, and Gd allows tailoring of TEC values to closely match nickel-based superalloys (Vakilifard et al., 2024). This reduces mismatch stresses, enhancing coating adhesion and resistance to spallation during thermal cycling.

Fracture Toughness and Creep Resistance

Mechanical robustness is equally important. HECOs exhibit improved fracture toughness compared to conventional ceramics due to lattice distortion and defect engineering. The presence of multiple cations generates local stress fields that impede crack propagation, enhancing toughness (The American Ceramic Society, 2024). Additionally, HECOs demonstrate superior creep resistance at high temperatures. Sluggish diffusion of cations slows deformation processes, allowing coatings to maintain structural integrity under sustained mechanical and thermal loads (Vakilifard et al., 2024). These properties are crucial for long-term durability in aerospace and energy applications.

Oxidation and Corrosion Resistance

High entropy ceramic oxides (HECOs) are increasingly recognized as promising candidates for thermal barrier coatings (TBCs) in advanced gas turbine engines. Their unique compositional complexity and entropy-driven stabilization confer superior resistance to oxidation and corrosion compared to conventional yttria-stabilized zirconia (YSZ). Key aspects of their performance include interaction with bond coats, resistance to calcium–magnesium–alumino–silicate (CMAS) attack, and hot corrosion behavior.

Interaction with Bond Coats

Bond coats, typically NiCoCrAlY alloys, serve as oxidation-resistant layers between the metallic substrate and ceramic topcoat. Compatibility between HECOs and bond coats is essential to prevent delamination. Studies have shown that HECOs exhibit reduced oxygen diffusivity due to sluggish cation diffusion, which slows the growth of thermally grown oxides (TGOs) at the bond coat interface (Vakilifard et al., 2024). This mitigates stress accumulation and enhances coating lifetime. Furthermore, entropy-stabilized oxides maintain phase integrity during thermal cycling, reducing mismatch stresses with bond coats compared to YSZ (Zhou et al., 2023).

Resistance to CMAS Attack

CMAS infiltration is a major degradation mechanism in turbine environments, where molten silicate deposits penetrate coatings, destabilizing phases and reducing durability. HECOs demonstrate superior resistance to CMAS attack due to their complex cation chemistry. Rare-earth-based HECOs, for example, hinder CMAS penetration by forming stable reaction layers that slow infiltration (Liu et al., 2025). The sluggish diffusion of multiple cations also reduces reactivity with CMAS, extending coating lifetimes. Compared to YSZ, which readily dissolves in CMAS melts, HECOs maintain structural integrity under prolonged exposure, making them attractive for high-demand aerospace applications.

Hot Corrosion Behavior

Hot corrosion, driven by molten salts such as Na_2SO_4 and V_2O_5, poses another challenge for TBCs. HECOs exhibit enhanced hot corrosion resistance due to their entropy-stabilized phases and reduced ionic mobility. The presence of multiple cations creates local lattice distortions that impede diffusion of corrosive species, slowing degradation (Vakilifard et al., 2024). Experimental studies on Zr-based HECOs have shown that coatings retain phase stability and resist salt-induced spallation better than conventional ceramics (Dudnik et al., 2021). This resilience is critical for turbine blades operating in marine or industrial environments where hot corrosion is prevalent.

Applications

Applications in Gas Turbines and Aerospace

High entropy ceramic oxides (HECOs) have emerged as transformative materials for advanced thermal barrier coatings (TBCs) in aerospace and energy systems. Their unique entropy-stabilized structures provide ultra-low thermal conductivity, high phase stability, and superior resistance to oxidation and corrosion, making them ideal for demanding environments such as jet engines, industrial gas turbines, and hypersonic vehicles.

Jet Engines

Modern jet engines operate at extremely high temperatures to maximize efficiency and thrust. Conventional yttria-stabilized zirconia (YSZ) coatings begin to degrade above 1200 °C, limiting performance. HECOs, by contrast, maintain phase stability beyond 1400 °C due to configurational entropy, enabling higher turbine inlet temperatures (Vakilifard et al., 2024). Their reduced thermal conductivity, often below 1.5 W/m·K, provides superior insulation compared to YSZ (Liu et al., 2025). Additionally, HECOs exhibit enhanced resistance to calcium–magnesium–alumino–silicate (CMAS) infiltration, a common degradation mechanism in jet engines, thereby extending coating lifetimes and reducing maintenance costs (Zhou et al., 2023). These properties make HECOs strong candidates for next-generation jet propulsion systems.

Industrial Gas Turbines

Industrial gas turbines used in power generation face similar challenges, including high operating temperatures, thermal cycling, and corrosive environments. HECOs offer significant advantages by reducing thermal conductivity and improving oxidation resistance. Their sluggish cation diffusion slows oxygen transport, minimizing thermally grown oxide (TGO) formation at the bond coat interface (Vakilifard et al., 2024). This compatibility enhances coating adhesion and durability under long-term operation. Furthermore, HECOs' tunable thermal expansion coefficients allow better matching with nickel-based superalloys, reducing thermal mismatch stresses during cycling (Liu et al., 2025). These attributes position HECOs as promising materials for improving efficiency and reliability in industrial turbines, particularly in environments with frequent load changes and corrosive fuel impurities.

Potential for Hypersonic Vehicles

Hypersonic vehicles present some of the most extreme material challenges, with surface temperatures exceeding 1500 °C due to aerodynamic heating. Conventional ceramics often fail under such conditions due to phase instability and poor mechanical compliance. HECOs, however, demonstrate exceptional thermal stability and mechanical robustness. Their entropy-stabilized phases resist transformation at ultra-high temperatures, while lattice distortions and defect engineering enhance fracture toughness and creep resistance (The American Ceramic Society, 2024). Moreover, HECOs' superior hot corrosion resistance against molten salts and silicate deposits makes them suitable for hypersonic flight environments, where both thermal and chemical stresses are severe. Research suggests that HECO-based coatings could enable reusable hypersonic vehicles by providing long-term protection against thermal shock and corrosive attack (Vakilifard et al., 2024).

Challenges and Limitations

High entropy ceramic oxides (HECOs) have attracted significant attention as next-generation thermal barrier coating (TBC) materials due to their ultra-low thermal conductivity, high phase stability, and superior corrosion resistance. However, despite their promising properties, several challenges and limitations hinder their widespread adoption in aerospace and energy applications. These include scalability of synthesis, cost and availability of rare earth elements, long-term durability, and the lack of standardized testing protocols.

Scalability of Synthesis

One of the primary challenges in HECO development is the scalability of synthesis. Laboratory-scale methods such as solid-state reaction, sol-gel processing, and spark plasma sintering have successfully produced HECOs with desirable properties (Liu et al., 2025). However, scaling these processes to industrial levels remains difficult due to the need for precise stoichiometric control across multiple cations. Maintaining uniform distribution of five or more elements during large-scale deposition, particularly in techniques like plasma spraying or EB-PVD, is complex and prone to phase segregation (Vakilifard et al., 2024). This limits the ability to produce consistent coatings for turbine components.

Cost and Availability of Rare Earth Elements

Many HECO compositions rely on rare earth elements such as La, Nd, Sm, and Gd to achieve ultra-low thermal conductivity and CMAS resistance. The cost and limited availability of these elements pose significant barriers to commercialization (Zhou et al., 2023). Global supply chain fluctuations and geopolitical factors further exacerbate the issue, making rare-earth-based HECOs economically challenging for widespread industrial use. Developing HECOs with more abundant transition metals or mixed compositions may help mitigate this limitation.

Long-Term Durability

Although HECOs exhibit excellent phase stability and corrosion resistance in short-term studies, their long-term durability under real turbine operating conditions remains uncertain. Extended thermal cycling, mechanical stresses, and exposure to corrosive environments may lead to microstructural degradation over time. For example, while sluggish cation diffusion enhances CMAS resistance, it may also slow healing mechanisms that mitigate crack propagation (Dudnik et al., 2021). Comprehensive durability testing is needed to validate HECOs' performance over thousands of operating hours.

Standardization and Testing Protocols

Another critical limitation is the lack of standardized testing protocols for HECOs. Conventional TBCs such as YSZ have well-established benchmarks for thermal conductivity, phase stability, and mechanical properties. In contrast, HECOs are relatively new, and testing methods vary widely across research groups (Vakilifard et al., 2024). Without standardized protocols, comparing results and validating performance across different compositions and deposition techniques is difficult. Establishing international standards for HECO characterization will be essential for industrial adoption.

Future Directions

High entropy ceramic oxides (HECOs) represent a promising frontier in thermal barrier coatings (TBCs) for aerospace and energy applications. While current research has demonstrated their superior thermal and mechanical properties, future directions emphasize advanced design methodologies, integration with complementary protective systems, and sustainable development.

AI-Guided Design of HECOs

Artificial intelligence (AI) and machine learning are increasingly applied to accelerate the discovery of novel HECO compositions. By analyzing large datasets of cation combinations, AI can predict thermophysical properties such as thermal conductivity, phase stability, and corrosion resistance (Vakilifard et al., 2024). This approach reduces reliance on trial-and-error experimentation and enables rapid identification of optimal compositions tailored for specific turbine environments.

Integration with Environmental Barrier Coatings

Future applications will likely involve integrating HECOs with environmental barrier coatings (EBCs) to protect against water vapor and corrosive gases in next-generation engines. HECOs provide thermal insulation, while EBCs mitigate chemical degradation, creating a synergistic multilayer system. Such integration could extend coating lifetimes in both jet engines and industrial gas turbines (Liu et al., 2025).

Multi-Scale Modeling

Multi-scale computational modeling, spanning atomic to macroscopic levels, will play a critical role in understanding HECO behavior. Atomistic simulations can reveal diffusion mechanisms, while finite element models predict coating performance under thermal cycling. This holistic approach bridges fundamental science and engineering practice, guiding both synthesis and application (Zhou et al., 2023).

Sustainable Material Development

Sustainability is another emerging priority. Many HECOs rely on rare earth elements, which are costly and subject to supply chain risks. Future research will explore compositions incorporating more abundant transition metals, reducing environmental impact and ensuring long-term material availability (Vakilifard et al., 2024).

Conclusion

High entropy ceramic oxides (HECOs) have established themselves as one of the most promising material innovations for thermal barrier coatings (TBCs) in aerospace and energy systems. Their unique entropy-stabilized structures enable ultra-low thermal conductivity, superior phase stability, and enhanced resistance to oxidation, corrosion, and CMAS infiltration compared to conventional ceramics such as yttria-stabilized zirconia (YSZ). These properties directly impact the efficiency and durability of gas turbines and jet engines, allowing higher operating temperatures and improved fuel economy.

The impact of HECOs lies in their ability to extend the operational envelope of propulsion and power systems. Their tunable thermal expansion coefficients improve compatibility with metallic substrates, reducing spallation risks during thermal cycling. Mechanical robustness, including improved fracture toughness and creep resistance, further enhances long-term durability under extreme service conditions. Collectively, these attributes position HECOs as strong candidates for next-generation aerospace applications, including industrial gas turbines and hypersonic vehicles, where conventional ceramics often fail.

Looking toward the next decade, several key directions will shape the future of HECOs. Advances in deposition techniques such as EB-PVD, plasma spraying, and additive manufacturing will be critical for scaling production while maintaining compositional uniformity. AI-guided design and multi-scale modeling are expected to accelerate the discovery of optimized HECO compositions tailored for specific environments. At the same time, sustainable material development will address challenges related to rare earth availability, ensuring economic and ecological viability. Establishing standardized testing protocols will also be essential to validate long-term performance and enable industrial adoptio

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THE ROLE OF MOBILE PHONES IIN ENHANCING FISH FARMING IN EDO NORTH SENATORIAL DISTRICT AUCHI METROPOLIS

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ABSTRACT

Mobile phones play a vital role in enhancement of fish farming business worldwide. This study examined the application of mobile phones by fish farmers in Edo North Metropolis, Edo State Nigeria. The objectives include assessing the socio-economic characteristics of the respondents, ascertaining the fish farming activities; access and application of mobile phones and constraints to the use of mobile phones by respondents. The research design was a survey in which data was obtained from 86 registered fish farmers in Edo North Senatorial District comprising of Etsako East Local Government Area, Agenebode, Etsako West Local Government Area, Auchi, Akoko - Edo Local Government Area, Igarra, Owen East Local Government Area, Afuze and Owen West Local Government Area, Sabogida - Ore, Edo State, Nigeria who were purposively selected for the study. The data obtained were analyzed using simple frequencies and percentages as well as means and Chi-Square statistics. The findings revealed that male fish farmers dominated with 69.8% and the mean age was 39 years. More so, majority of the respondents had access to mobile phones which were utilizes in obtaining information such as feed, new trend, credit facilities, fingerlings, equipment, storage, drugs, disease control and treatment. However, the use of mobile phones was constrained by the problem of high call tariff, erratic power supply and fluctuating services. The study recommended that appropriate national telecommunication policy and regulation should be put in place that will bring down high tariff charged by mobile telecommunication companies and provision of adequate power supply to enhance fish farming production in the Metropolis.

Keywords: Mobile phones, Fish farming, Telecommunications

Introduction

The advent of information and communication technology (ICT) and its subsequent adoption by both the developed and developing countries ushered in the information age. Consequently, information has become a valuable commodity in the global world where nations that have acquired the necessary ICT infrastructures have been moving rapidly into the post-industrial information-based economy. These can under certain conditions help to improve the living conditions of the rural people through better and more sustainable livelihoods strategies (United Nation, 2025). Mobile phone which is an integral part of ICT has become one of the most important media of information communication

Of our time. According to Spore (2025), half of the world's 6.5billion people now use a mobile telephone, compared with 2 billion just two years ago. In Africa, mobile phone business is the most rapidly growing sector of the economy with over 120 subscribers). According to Adogla (2025), the annualized aggregate growth rate in handset number was pegged at a healthy 58%, a figure that clearly propelled the Africa cellular market to outperform all others worldwide.

introduction of mobile phones in agricultural sector has brought about drastic changes which have helped farmers to be able to access information with ease. Also, reasonable pricing and easy access have helped make this technology a potential tool for generating economic opportunities and social networking, even in rural areas (e-agricutlure.org, 2026). Therefore, the role of fish farming in achieving household and national food security and poverty alleviation cannot be overemphasized (Salau, Lawee, Luka, & Bello, 2013).

However, the fact remains that at various levels of human endeavours, good communication is absolutely imperative, also information as a factor of production is necessary to increase productivity. Fisheries offer a key entry point to reach millions of poor people of Africa, including Nigeria, to assist in increasing people's income, improving the nutrition and health of families and becoming active agents of economic development and social change (Bene & Hecks, 2005). Women make up the greater percentage of people involved in agriculture in Nigeria but women farmers are naturally more handicapped, with lower education, less access to land, labor, information and technology (NHDR, 2025). Education on the other hand, raises income as it enables individuals to obtain and process information (Knight & Lina, 2023; World Bank, 2023). No wonder Angba, *et al.,* (2019) found that educational level correlates significantly and positively with age. As pointed out by Ekong (2023), there is also a positive correlation between Nigerian farmers' level of participation in social organization and

In Nigeria, the introduction of Global System for Mobile Communication (GSM) in 2001 marked the positive contribution of telecommunication to social activities of the people (Philip, 2020). The adoption of agricultural innovations as several studies showed that Nigerian farmers belong to a number of formal and informal organizations. Meanwhile, lack of access to land; credit, education, and other production input, as well as farm experience limit farmers' earning capacity (Dorosh, Haggblade, Rajemison, Bodo, & Simmler, 2023).

In the fishery subsector, mobile phones are used to coordinate fishing effort; product marketing as well as safety. Nigeria is reported to have aquaculture potential which constitutes 75% of 923,768km^2 of the landmass and 14million hectares of inland fresh water, but less than 1% is utilized for fish production (Ugwumba & Ugwumba, 2023; and Food and Agricultural Organisation, FAO, 2025). The report further revealed that aquaculture is dwarfed by fish importation, an indication of poor exploitation of aquaculture resources capable of producing over 3 million tonnes of fish to meet domestic demand and excess for export (Ifejika, Akinbile, Ifejika, & Oladeji, 2025). Applying proven technology will increase production of small scale operators that constitute 80% of global fish farmers (New Partnership for Africa Development, (NEPAD), 2025; Gupta, 2026). Information on improved aquaculture technologies and its resultant effect on productivity and income of fish farmers need to be investigated. The search for an effective strategy for agricultural development calls for adequate use and application of mobile phones.

Fish farmers need information to enhance agricultural management, research and development (Nkwocha, Ibeabuchi, Chukweke, Azubuike, & Nkwocha, 2025). Access to information is very essential for

e the current divide between the rural and the urban areas in order to help improve the living standard of the fish farmers and agricultural production call for the adequate application of mobile phones by fish farmers in the study area. Thus, the major objective of this study was to examine how to enhance fish farming with the application of mobile phones by fish farmers in Edo North Metropolis, Edo State. The specific objectives were to examine the socio-economic characteristics of the fish farmers, discuss fish farming activities in the study area, ascertain the application of mobile phones by fish farmers and examine the constraints to the application of mobile phones by fish farmers. A null hypothesis was stated that “There is no statistically significant effect of socio-economic variables on application of mobile phones by fish farmers.

Theoretical and empirical Framework

This study was well informed by two theories of adoption and innovation of Information and communication technology (ICT) in teaching and learning processes in education namely: Marcus's Theoretical Model of Adoption and Diffusion of Innovation Theory. The Marcus's Theoretical Model of Adoption according to Ankem (2024) was derived from the diffusion of innovation theory and the social learning theory. This model highlights the importance of innovative behaviour and the phenomenon of others modeling themselves on this. Communication channels are a vital component in enhancing this modeling

characteristics, and opinion leadership. Based on this guideline investigation was done on the socio-economic factors and personality

has introduced a new search technology that offers several advantages over other alternatives in terms of cost, geographic coverage and ease of use (Aker & Mbiti 2020). The reduction in search costs associated with mobile phones could increase

increased productivity by fish farmers (Ugboma, 2010). Therefore, the need to bridg behavior to other potential adopters. According to Ankem, the model explores three major influential factors in the take-up of innovations including the associated 'costs' - personal and institutional, the availability of necessary 'resources' - money, equipment, training, time, prior experience and relevant skills and the 'value' of the innovation-this illustrates the need to bring together a mix of personal and institutional factors for optimal take-up of innovations. Those factors relating to the institutions' ability to provide the conditions conducive to the introduction and acceptance of innovations could be used to map out an institutional framework for adoption. This theory therefore guided in the investigation of the factors hindering the application of mobiles by fish farmers in Edo North Metropolis.

On the other hand, Diffusion of Innovation Theory according to Perry (2024) was a process through which some innovation is communicated within a social system. Perry introduces the idea that 'time' is an important factor in the rate of diffusion. He also stresses the role of individuals and their social influence in the diffusion process. Scholars, like Rogers, who study communication, have concentrated on more theoretical approaches. Rogers' diffusion of innovation theory incorporates the innovation-decision process, innovation characteristics, adopter

values of the respondents. The rapid growth of mobile telephony in developing countrie

farmers’ access to information via their private sources, such as members of their social network (Baye, Morgan, & Scholten, 2024, Aker & Mbiti 2020). Several studies have highlighted the importance of risk and supply-side constraints as barriers to agricultural technology adoption. Simple mobile phones can be used as a means of collecting both farmer and agent-level data, thereby improving the accountability of extension services (Dillon 2023). A mobile application is a piece of software on a phone table device (such as a mobile phone handset, personal digital assistant or tablet computer) that enables a user to carry out functions or more specific tasks that are not directly related to the operation of the device itself. Market Information Services or MIS, are information systems used in gathering, analyzing and disseminating information about prices and other information relevant to farmers, traders, processors and others involved in handling agricultural products.

In education, mobile phones have come up with the concept of m-learning. The term "learning" or "mobile learning, has different meanings for different communities. Although related to e- learning and distance education, it is distinct in its focus on learning across contexts and learning with mobile devices. Mobile learning is a sort of learning that happens when the learner is not at a fixed, predetermined location, or learning that happens when the learner takes advantage of the learning opportunities offered by mobile technologies. Another study was conducted in

Ghana where mobile phones were introduced among farmers for communicating with traders and representatives for selling their bananas in advance and negotiate with customers and get high price. In this context, they save their money, time and energy (Muto, & Yamano, 2021). Typically involves using small boat and canoes, it accounts for more than 25% of the world catch it is the source Of more than 40% of the fish used for human consumption. This sector provides the bulk of the fish consumed in Africa. Fish farming is the least exploited fishery subsector with the vast brackish water fishing grounds almost unexploited (Ejiola & Yinka, 2022). Nigeria has good potential for aquaculture development and thus potential can be realized substantially through extension services (Adetunji, 2021). By provision of mobile phones to fish farmers, which will make them to have access to agricultural information without much hindrance, which will help in improving the economy.

Methodology

The study was conducted in Edo North Metropolis comprising of Etsako East Local Government Area, Agenebode, Etsako West Local Government Area, Auchi, Akoko - Edo Local Government Area, Igarra, Owen East Local Government Area, Afuze and Owen West Local Government Area, Sabogida - Ore, Edo State. Indigenes are Etsako, Owen and Igarra known for their artistic skills, rich food, culture and tradition. Main occupation is agriculture and the bulk of farmers are subsistent. Soil type is dark and vegetable crops like pumpkin and tuber crops like cassava are majorly grown in Edo State. Other crops include groundnut, palm fruit, maize, pepper, okra, etc. (Ushie, 2026)

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The study population comprises of a total of 170 registered fish farmers in Edo North Metropolis made of 73 registered fish farmers at Edo North and 97 registered fish farmers at Auchi Municipality. Simple random sampling technique was adopted in selecting respondents for the study. For the purpose of the research work, fish farmers with odd numbers as seen in the list of registered fish farmers in the sample frame were selected, making a total of 86 fish farmers. Structured questionnaires were distributed to the respondents to elicit information. Both description and inferential statistical tools were used to analyze the data. The descriptive statistical tools used were simple frequencies, percentages and in addition to the use of chi- square statistics. The application of mobile phones by fish farmers was the dependent measured using the score given for frequency of application of mobile phones. Independent variables include age, sex, income, educational qualification and farming experience. Inferential statistics (chi-square) goodness of fit was used to test the hypothesis. Formula is given

$$X^2 = \sum \frac{(O - E)^2}{E}$$

Where: O = Observed value,
E = Expected value
∑ - Summation of values

Results and Discussions

The results of the study are discussed in this section

Table1: Distribution of respondents by Sex

	Frequency	**Percentage (%)**
Male	60	69.8
Female	26	30.2
Total	**86**	**100.0**

Source: Field survey, 2026

Result of table 1 shows male dominance in fish farming activities accounting for 69.8% while female fish farmers represent only 30.2%, implying that majority of the respondents are male. This might be due to the tedious nature of fish farming especially as many of them spent sleepless nights at the rivers. On the other hand, female fish farmers faced a lot of challenges than as compared to their male counterparts. This result confirmed studies (NHDR, 2008) that even though women make up the greater percentage of people involved in agriculture in Nigeria but women farmers are naturally more handicapped, with lower education, less access to land, labor, information and technology

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Table 2: Distribution of respondent according to age

Age	**Frequency**	**Percentage (%)**
21-30 years	4	4.7
31-40 years	42	48.8
41-50 years	18	20.9
51-60 years	11	12.8
61-70 years	9	10.5
71years& above	2	2.3
Total	**86**	**100.0**

Source: Field survey, 2026

Table 2 shows the age category of respondents where age group of 31-40 years recorded the highest frequency 42(48.8%) showing that farmers within the age group are still in their prime full of vigor and energy while the least was 71years and above with 2 (2.3%) indicating older farmers who are retiring from fish farming activities. This result confirmed studies by Angba, *et al.*, (2009) which found that educational level correlates significantly and positively with age

Table 3: Distribution of Respondents by Marital Status

Marital status	Frequency	Percentage (%)
Single	30	34.9
Married	37	43.0
Divorcee	4	4.7
Widow	6	7.0
Widower	5	5.8
Separated	4	4.7
Total	**86**	**100.0**

Source: Field Survey, 2026

Table 3 results indicate the marital status of respondents with married fish farmers accounting for 43.0% whereas separated farmers recording only 4.75%. This result shows that majority of the respondents are married.

Table 4: Distribution of respondents by educational qualification

Educational Qualification	Frequency	Percentage (%)
No formal education	23	26.7
Primary education	22	25.6
Secondary education	29	33.7
Post-Secondary education	12	14.0
Total	**86**	**100.0**

Source: Field survey, 2026

Table 4 above shows the distribution of educational qualification among respondents. Majority of the fish farmers had secondary education with 33.7% while those with post-secondary education had the least of 14.0%. Education is a veritable tool for enhancement of fish farming activities. Result therefore was in line with earlier studies which stated that education helps to raise income as it enables individuals to obtain and process information (Knight *et al*., 2003; World Bank, 2008).

Table 5: Membership From table 4.5, 55.8% of the respondents are member of organization, while 44.2% are not member in any organization. Therefore most of the fish farmers are members of social organizations. This result is in line with Ekong (2023) which reported a positive correlation between Nigerian farmers' level of participation in social organization and adoption of agricultural innovations as several studies showed that Nigerian farmers belong to a number of formal and informal organizations

of organizations

Membership of Organization	Frequency	Percentage (%)
Yes	48	55.8
No	38	44.2
Total	**86**	**100.0**

Source: Field Survey, 2026

Table 6 Distribution of respondents based on Annual Income

Annual income	Frequency	Percentage(%)
#50,000-#80,000	37	43.0
#81,000-#110,000	23	26.7
#111,000-#140,000	17	19.8
#141,000-#1700,000	6	7.0
#171,000-#200,000	3	3.5
Total	**86**	**100.0**

Source: Field Survey, 2026

The distribution on table4.6 shows that 43.0% of the respondents earn between #50,000 - #80,000, 26.7% of the respondents earn between #81,000 - #110,000, 19.8% of the respondents earn between #111,000 - #140,000; 7.0% of the respondents earn between #141,000 - 170,000 while 3.5% of the respondents earn #171,000 - #200,000. The result shows that there is need for improvement in catches to improve upon annual income of fishermen thereby agreeing with the result of earlier studies that lack of access to land, credit, education , and other production input, as well as farm experience limit farmers' earning capacity (Dorosh, *et al*, 1998).

Table 7: Distribution of respondents by fish farming experience

Fish farming experiences	Frequency	Percentage (%)
6-10years	11	12.8
11-15years	23	26.7
16-20years	12	14.0
21-25years	14	16.3
26-30years	9	10.5
31-35years	7	8.1
36-40years	10	11.6
Total	**86**	**100.0**

Sources: Field survey, 2026

The result of table7 above shows that 11-15 years was the highest years of fish farming experience by farmers (26.7%) followed by 21-25 years (16.3%) while the least years were 31- 35 years (8.1%

Table 8: Distribution of respondents by access to mobile phones

Ownership of mobile phones	Frequency	Percentage (%)
Yes	78	90.7
No	8	9.3
Total	**86**	**100.0**

Source: Field survey, 2026

The result of table 8 above shows that 90.7% of the respondents had personal mobile phones while only 9.3% does not own a mobile phone. In conclusion majority of the respondents owned mobilephone

Table 9: Distribution of respondents by access to mobile phones

Access to mobile phones	Frequency	Percentage(%)
Access to owned phone	78	90.7
Access to Neighbors	3	3.5
Access to Friends	5	5.9
Total	**86**	**100.0**

Source :Field survey, 2026

Table 9shows the distribution of respondents' access to mobile phones. It was revealed that 90.7% had personal mobile phones, 3.5% had access to mobile phones through their neighbors, of mobile phones while 5.9% had access to mobile phones through their friends.

Table 10: Distribution of respondents based on the application

S/N	Application of mobile phone	SA	A	N	D	SD	Total	Mean	Average mean
1	Feed	60	14	2	1	9	86	4.34	3.44
2	New trend	31	19	10	9	17	86	3.44	3.44
3	Disease control/treatment	29	17	11	12	17	86	3.34	3.44
4	Credit facilities	22	23	9	17	15	86	3.23	3.44
5	Equipment	27	16	9	15	19	86	3.20	3.44
6	Drug	28	18	7	12	21	86	3.23	3.44
7	Fingerlings	33	20	6	10	17	86	3.49	3.44
8	Government/private involvement	22	9	9	19	27	86	2.77	3.44
9	Storage	52	12	2	7	13	86	4.00	3.44
	Total								**31.01**

Source: Field Survey, 2026

A five-point Likert scale was used to analyze the application of mobile phones by respondents. A mean score of 3.44 was used as the average mean to appraise the application of mobile phones by the respondents. All values above 3.44 indicate high application of mobile phones while values below 3.44 indicate less application of mobile phones. However, mobile phones were highly applied in getting information such as feed(4.34),new trend (3.44),fingerling(3.49) and storage (4.00) whereas the less areas of application of mobile phones were in disease control/ treatment(3.34),credit facilities (3.23),equipment(3.20),drug (3.23) and government/ private involvemen

(2.77)

Table 11:Distribution of respondents by constraints to application of mobile phones

S/N	Constraint of application of mobile phones	SA	A	N	D	SD	Total	mean	Average mean
1	High cost of mobile phone	45	28	2	6	5	86	4.19	3.61
2	Fluctuating services	37	38	4	4	3	86	4.19	3.61
3	Erratic power supply	31	29	9	12	5	86	3.80	3.61
4	Repairs of technical fault	24	18	11	24	9	86	3.28	3.61
5	High cost of call charges	23	16	5	23	19	86	3.01	3.61
6	Access to recharge purchasing centre	24	12	5	20	25	86	2.88	3.61
7	Mobile phones can sometimes fall into sea/ pond	44	14	3	15	10	86	3.78	3.61
8	Mobiles phones are attractive to thieves	50	10	1	9	16	86	3.80	3.61
	Total								**28.93**

Source: Field Survey, 2026

The result of the five-point Likert scale shows the constraints to application of mobile phones by respondents where a mean score of 3.6 and above indicate a constraint while a mean score of less than 3.6 indicate no constraints. However, constraints include high cost of mobile phone(4.19),fluctuating services(4.19),erratic power supply(3.80), and fallen phones into the sea(3.78). On the other hand, age, educational level, farming experience and annual income were significant socioeconomic characteristics that can enhance the application of mobile phones by fish farmers in their fishing activities.

Conclusion and recommendations

The study assessed the enhancement of the application of mobile phones by fish farmers in Auchi Metropolis, Edo State, Nigeria. The findings of the study showed that fish farmers had access to mobile phones, and that mobile phones were not only adopted for social reasons, but were viewed by the farmers as a tool that allowed for more efficient response to economic opportunities.

Recommendations are made that age, education, farm experience and annual income are critical factors necessary for the enhancement of the application of mobile phones in fish farming activities and should be seriously encouraged. There should be improved electricity supply to enhance production.

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SUSTAINABLE WEED MANAGEMENT STRATEGIES IN SMALL HOLDER FARMING SYSTEMS

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ABSTRACT

Weed competition significantly reduces crop productivity and farmer income in smallholder farming systems worldwide. Conventional weed control methods often rely on synthetic herbicides, which may be costly and environmentally damaging. Sustainable Weed Management (SWM) integrates ecological principles with cultural, mechanical, biological, and limited chemical strategies to effectively manage weed populations while enhancing agroecosystem health. This paper reviews key sustainable strategies, including crop rotation, cover cropping, mulching, mechanical weeding, and integrated weed management frameworks. Evidence suggests that diversified and knowledge-based approaches reduce weed pressure, improve soil fertility, and enhance long-term productivity. The study concludes that integrated, locally adapted weed management strategies offer viable and resilient solutions for smallholder farmers.

Keywords; Sustainable, Weed Management, Smallholder, Farming, System.

Introduction

Weeds are plants that compete with crops for essential resources such as water, nutrients, sunlight, and space. In smallholder farming systems, particularly in developing regions, weed infestation remains one of the most significant constraints to agricultural productivity. Limited access to herbicides, labour shortages, and inadequate extension services further complicate weed control efforts. Sustainable Weed Management (SWM) provides an ecologically sound and economically feasible alternative to heavy herbicide dependence (Chauhan and Johnson, 2020).

In the years ahead, agriculture, especially smallholder farming in developing countries, will encounter multiple overlapping challenges. These include rapid population growth, rising migration, labour shortages, declining land productivity, climate instability, and increasing food insecurity. Ensuring sustainable food and agricultural systems requires protecting natural resources. However, intensive farming practices have significantly degraded soils, threatening their long-term productivity and putting future food supplies at risk in these regions (Norris, 2019).

Much needs to be done to prevent further losses and to enhance the status of natural resources. Food insecurity and poverty are significant development challenges and have fueled migration from rural to urban centres; while this has been occurring for centuries, it is now an accelerating phenomenon. Moreover, arduous farm work and environmental degradation of the land are driving more youth to the towns seeking better opportunities, but often facing unemployment and further hardship. Urbanization in low-income countries is often accompanied by high levels of poverty, unemployment and food insecurity (Bond and Grundy, 2021).

The direct impact that urban migration brings to rural areas is the loss of workforce for agricultural tasks, which immediately affects productivity. Smallholder agriculture has certain labour peaks, among these is timely weeding, an important determinant of whether yields will be maintained or decreased. Mechanical weeding by human labour power (hoeing, scraping, roguing, uprooting) is a laborious undertaking. Furthermore, the timeliness of the operation is a critically important factor, often requiring farm families to work long hours. This can limit the availability of farm labour for hand weeding, leading smallholders to limit their areas under production, governed by the affordability and availability of labour at peak times. In turn, the pressure for the youth to engage in farming is high, despite the fact that the agricultural sector is unattractive for this demographic (Noris, 2019).

Due to the high dependence on hand labour for weeding (and, often, primary land preparation), it is clear why both land and labour productivity remain at a low level. Continuous hand hoeing for weeding and land preparation are among the main causes for losses of soil organic matter (SOM). Experience shows that constant ploughing and hoeing can lead to the loss of soil fertility, mainly due to the oxidation of SOM and the exposure of bare soils to sun, wind and rain that cause run-off and surface erosion of the fertile top soil. This eventually makes soils unusable for farming (**Basch et al., 2022)**.

Therefore, the question for many farmers is: what are the sustainable alternatives for crop production intensification? Conservation agriculture (CA) is a response to sustainable land management, environmental protection and climate change adaptation and mitigation. It promotes maintenance of a permanent soil cover, minimum soil disturbance, and diversification of plant species. It enhances biodiversity and natural biological processes above and below the ground surface, which contribute to increased water and nutrient use efficiency and to improved and sustained crop production. However, weed management may be critical for successful implementation of CA (Noris, 2019).

Fortunately, there are practical strategies that can lower weed pressure while recognizing that the aim is effective weed management rather than complete eradication. In some cases, allowing a limited presence of weeds can support beneficial functions within the agroecosystem. Although weeds must still be controlled—particularly during critical growth stages of the main crop—alternatives to mechanical hoeing, such as applying crop residues or mulch, can effectively suppress their growth. Additionally, intercropping with selected leguminous crops can further reduce weed competition. By addressing one of the major constraints in smallholder farming—labour-intensive hand weeding—through improved agronomic practices and appropriate technologies, agriculture could become more appealing to rural youth (**Lee and Thierfelder, 2017)**.

This paper reviews the applicability and efficacy of various mechanical, biological and integrated weed management strategies for the effective and sustainable management of weeds in smallholder CA systems, including the role of appropriate equipment and prerequisites for smallholders within a sustainable intensification scenario.

Literature Review

Weed ecology studies indicate that disturbed soils and monocropping systems encourage weed establishment. Conventional herbicide-based systems, although effective in the short term, have led to herbicide resistance and environmental concerns. Integrated Weed Management (IWM) combines multiple control tactics to

sustainably
reducing e

The Challenge of Weeds in Smallholder Farms

Weeds compete with crops for water, nutrients, light, and space, leading to yield losses that can range from 10% to 80%, depending on weed intensity and crop type (Oerke, 2019). In many developing countries, smallholder farmers rely heavily on hand weeding**,** which is a labour-intensive and time-consuming farm practice. Climate change and labour migration further reduce the availability of labour, making traditional weed control practices less feasible (Akobundu, 2021).

Weeds are among the most significant constraints to crop production in smallholder farming systems, particularly in developing countries where access to herbicides and mechanization is limited. They compete directly with crops for essential resources such as light, nutrients, water, and space, which can lead to considerable yield reductions. Oerke (2019) highlighted that weeds are responsible for substantial crop losses worldwide, with yield reductions that can vary from 10% to over 80%, depending on the crop, weed species, and environmental conditions.

In smallholder settings, dependence on manual labour for weed control is common. Hand weeding is labour-intensive, time consuming, and typically carried out during peak agricultural seasons when labour demand is already high. This labour burden places a strain on farming households, especially where rural-to-urban migration is reducing available labour. Midega et al. (2022) note that labour scarcity due to migration and competing income opportunities is increasingly limiting the capacity of smallholder farmers to carry out timely weed management practices.

Furthermore, repeated tillage for weed removal can degrade soil structure and increase the risk of erosion, undermining long-term soil health (Unger and Vigil, 2020). In many smallholder systems, where soils are already vulnerable due to poor fertility and lack of organic matter, the combined effects of weeds and unsustainable weed removal practices exacerbate productivity challenges.

The weed seed bank—the reserve of viable weed seeds in the soil—is another significant issue. Once established, weed seed banks can persist for many years, making control difficult without integrated strategies that reduce seed production and weed germination (Radosevich et al., 2017). High weed pressure, limited resources, and the absence of affordable management technologies thus make weeds a persistent and costly challenge for smallholder farmers (Knezevic, et al., 2017).

Sustainable Weed Management Strategies

Crop Rotation and Diversification

Crop rotation disrupts weed life cycles and reduces species adapted to specific cropping environments. Alternating cereals with legumes modifies canopy structure and resource competition, thereby limiting weed growth and seed bank accumulation.

Crop rotation and diversification are essential components of sustainable weed management in smallholder farming systems. These practices disrupt weed life cycles, improve soil fertility, and reduce reliance on herbicides and intensive tillage.

i. *Crop Rotation*

Crop rotation involves growing different crops sequentially on the same piece of land across seasons or years. Rotating crops with different growth habits, planting dates, and nutrient requirements alters field conditions

And prevents specific weed species from becoming dominant.

Many weeds are adapted to particular crops and management systems; therefore, continuous monocropping often leads to the buildup of certain weed populations (Pretty et al., 2021).

Research shows that diverse crop rotations can significantly reduce weed density and weed seed banks by interrupting reproductive cycles and reducing seed production. For example, alternating cereals with legumes changes canopy structure, planting time, and soil disturbance patterns, which can limit the success of weeds adapted to a single cropping system. Additionally, some crops exhibit allelopathic properties—releasing natural chemicals that suppress weed germination (Mortensen, et al., 2022).

ii. *Crop Diversification*

Crop diversification goes beyond rotation and includes practices such as intercropping, mixed cropping, and the integration of cover crops. Intercropping which is the growing two or more crops simultaneously can suppress weeds by increasing ground cover and competition for resources. Leguminous intercrops, in particular, contribute to weed suppression while enhancing soil nitrogen through biological fixation.

Cover crops also play an important role in diversified systems. When grown during fallow periods, cover crops protect soil from erosion and suppress weeds by shading the soil surface and forming mulch residues after termination. This reduces weed emergence and helps manage the soil seed bank over time.

Cover Cropping

Cover crops suppress weeds through shading and resource competition. Additionally, they improve soil organic matter, structure, and moisture retention. Properly selected cover crops can significantly reduce weed emergence while enhancing soil fertility.

Cover cropping is a sustainable agricultural practice that involves growing specific crops primarily to protect and improve the soil rather than for harvest. In smallholder farming systems, cover crops play a vital role in weed management, soil conservation, and overall farm productivity.

Role of Cover Crops in Weed Suppression

Cover crops suppress weeds through several ecological mechanisms. First, they compete directly with weeds for light, water, nutrients, and space. Fast-growing species form dense canopies that reduce sunlight reaching the soil surface, thereby limiting weed seed germination and growth (Basch, et al., 2022).

Second, after termination, cover crops leave residues that act as mulch. This mulch layer forms a physical barrier that inhibits weed emergence and reduces the size of the weed seed bank over time. Some cover crops, such as rye and certain legumes, also exhibit allelopathic properties, releasing natural compounds that suppress weed germination (Unger and Vigil, 2020).

Types of Cover Crops Used in Smallholder Systems

Smallholder farmers commonly use:

- **Leguminous cover crops** (e.g., cowpea, mucuna, clover), which fix atmospheric nitrogen and improve soil fertility.
- **Grasses** (e.g., rye, sorghum), which provide substantial biomass for mulching and effective ground cover.
- **Mixed species cover crops**, which combine legumes and grasses to maximize both soil fertility and weed suppression.

climate, soil conditions, cropping system,

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Mulching

Organic mulches, including straw and crop residues, block sunlight and physically suppress weed growth. Mulching also contributes to soil health by adding organic matter and improving microbial activity.

Mulching is a sustainable weed management practice that involves covering the soil surface with organic or inorganic materials to suppress weed growth and improve soil conditions. In smallholder farming systems, mulching is particularly valuable because it reduces reliance on labour-intensive hand weeding and minimizes soil disturbance.

Mulch suppresses weeds primarily by blocking sunlight from reaching the soil surface, which prevents or reduces weed seed germination (Teasdale and Mohler, 2000). A sufficiently thick mulch layer acts as a physical barrier, limiting the emergence of weed seedlings. Organic mulches such as crop residues, straw, leaves, or grass clippings gradually decompose and may also release allelopathic substances that inhibit weed growth. Additionally, mulching helps manage the soil weed seed bank by reducing favourable conditions for germination and lowering weed seed survival over time (Teasdale and Mohler, 2000).

Mechanical Weed Control

Manual weeding and mechanical cultivation remain common in smallholder systems. When properly timed, these methods effectively reduce weed biomass and prevent seed production, although labour requirements may be high.

Mechanical weed control refers to the physical removal or destruction of weeds using manual tools, animal-drawn implements, or machinery. In smallholder farming systems, it remains one of the most widely practised weed management methods due to limited access to chemical herbicides and mechanised equipment (**Kayeke et al.** 2017)

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Common Mechanical Methods in Smallholder Systems

The most common mechanical methods include:

- **Hand weeding** using hoes or cutlasses
- **Hand pulling** of weeds
- **Animal-drawn cultivators**
- **Mechanical tillage or shallow cultivation**

Hand weeding is particularly dominant in smallholder agriculture across Africa, Asia, and Latin America. Although effective when done timely, it is highly labour-intensive and often accounts for a significant portion of total farm labour (Duke, 2022).

Integrated Weed Management

Integrated Weed Management combines ecological knowledge with multiple control methods tailored to specific farming contexts. Monitoring weed populations and applying control measures based on economic thresholds enhances long-term sustainability. Integrated Weed Management (IWM) is a holistic and sustainable approach that combines multiple weed control strategies to maintain weed populations below economically damaging levels while minimizing environmental harm. Rather than relying on a single method such as herbicides or intensive tillage, IWM integrates cultural, mechanical, biological, and, where appropriate, chemical practices based on ecological principles (Lee and Their felder, 2017)

Components of IWM in Smallholder Farming

1. Cultural Practices

Crop rotation, intercropping, optimized planting density, and timely sowing enhance crop competitiveness and reduce opportunities for weed dominance (Liebman & Dyck, 2023). Cover crops and mulching further suppress weed emergence through shading and physical barriers.

2. Mechanical Control

Hand weeding and shallow cultivation are often integrated with cultural practices to control weeds during critical crop growth stages. While labour-intensive, mechanical methods provide immediate weed suppression when properly timed.

3. Biological Control

Biological agents such as insects, pathogens, or competitive plant species can help regulate specific weed populations. Although less widely adopted in smallholder systems due to limited access and technical knowledge, biological control supports ecological balance.

4. Judicious Use of Herbicides

Where accessible and affordable, selective and limited herbicide use may be incorporated into IWM programs. Proper timing, dosage, and rotation of herbicide modes of action reduce the risk of resistance development. However, in many smallholder contexts, chemical inputs are either unavailable or used sparingly due to cost constraints.

Benefits of IWM for Smallholder Systems

Integrated Weed Management offers several advantages:

- Reduces dependence on any single control method
- Lowers long-term production costs
- Improves soil health and biodiversity
- Decreases environmental pollution
- Enhances resilience to climate variability

By combining low-cost ecological methods with targeted interventions, IWM can reduce labour burdens and increase productivity, making farming more attractive and sustainable for rural households (Teasdale and Mohler, 2023).

Discussion

Sustainable weed management strategies improve long-term productivity while protecting environmental resources. However, adoption barriers such as labour constraints, limited knowledge, and lack of policy support must be addressed through training programs and institutional support mechanisms.

Conclusion

Sustainable weed management is an integrated approach that minimizes herbicide use and addresses the challenges posed by weed competition, playing a crucial role in supporting sustainable crop production for a growing global population. It encompasses a range of strategies, including ecological practices that avoid chemical herbicides. The core principle is to prevent weed proliferation before they cause significant crop damage, rather than attempting to eliminate them once they are established. Complete eradication of weeds is not always the goal; instead, the focus is on managing weed populations so that their impact on productivity remains minimal.

A key aspect of this approach is promoting high biodiversity through practices such as crop rotations and intercropping, as well as encouraging natural populations of weed and seed predators. Cereal-legume combinations and agroforestry systems are particularly valuable in this context, offering both ecological and agronomic benefits.

There are numerous examples of successful ecological weed management. Leguminous cover crops serve as a prime illustration, as does the 'push-pull' strategy, which simultaneously manages weeds and insect pests using crops themselves. Such approaches demonstrate the potential for innovative, multifunctional farming practices.

Conventional soil tillage, in contrast, is generally incompatible with sustainable weed management. Implementing these strategies requires farmers to view crops as functional tools for agronomic inputs, partially replacing the role of chemical fertilizers and herbicides. This approach is knowledge-intensive and demands a significant shift in farm management practices and farmer mindset, which can be challenging to achieve. Consequently, sustained capacity-building and extension support are essential to encourage adoption.

Ultimately, sustainable weed management relies on a “many little hammers” approach—combining multiple small strategies—rather than the heavy reliance on herbicides as a single, dominant solution.

Sustainable Weed Management provides resilient alternatives to herbicide-dependent systems in smallholder farming. By integrating crop diversification, cover cropping, mulching, mechanical control, and informed chemical use, farmers can reduce weed pressure while enhancing soil health and productivity.

Recommendations

This paper recommends the following:

- Adopt Integrated Weed Management (IWM) by combining cultural, mechanical, biological, and selective chemical methods rather than relying on a single control strategy.
- Implement crop rotation and diversification to disrupt weed life cycles, enhance soil fertility, and reduce the dominance of specific weed species.
- Use cover crops during fallow periods or between main crops to suppress weed growth, improve soil organic matter, and fix nitrogen in the soil.
- Apply mulching with crop residues or organic materials to block sunlight, reduce weed emergence, conserve soil moisture, and prevent erosion.
- Conduct mechanical weed control, such as timely hand weeding or shallow cultivation, particularly during critical crop growth stages.
- Promote agroecological practices, including intercropping cereals with legumes and integrating agroforestry, to increase biodiversity and enhance natural weed suppression.
- Train farmers on ecological weed management strategies, such as push-pull systems and using functional crops to manage weeds and pests simultaneously.
- Limit the use of chemical herbicides to selective, minimal applications, ensuring proper timing and rotation to prevent resistance and environmental harm.
- Strengthen farmer knowledge and capacity through extension services, field schools, and participatory learning programs to encourage adoption of sustainable practices.
- Establish a system of monitoring and evaluation to track weed populations, crop performance, and soil health, allowing farmers to adapt strategies for better long-term outcomes
- .

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Beneficial Bacterial Metabolites as Virulence-Modulating Agents in the Suppression of Rice Bacterial Blight

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ABSTRACT

One of the major limiting factors to the global production of rice is rice bacterial blight (BB), a disease caused by the pathogen *Xanthomonas oryzae pv. oryzae* (Xoo), which leads to massive losses in yields. Conventional measures of control like host resistance genes and chemical bactericides have not been fully effective in curbing this disease because of pathogen adaptation, environmental conditions and limiting restraint laws. A more suitable option, presented as beneficial bacteria which may help inhibit rice BB through metabolite-based virulence suppression and priming of the host immune is proposed. The summary of mechanistic and field level data in this review indicates interferences in T3SS, TAL effector activity, iron capturing, DSF signaling and extracellular polymerization activity by bacterial metabolites; including lipopeptides, siderophores, antibiotics, quorum sensing enzymes, volatile organic compounds and biofilm-modulating polymers. Strains that have been tested and exhibited some of the best metabolite abilities in greenhouse and field conditions include *Bacillus velezensis*, *Bacillus atrophaeus*, as well as consortia of rice-related rhizobacteria, reducing disease levels by 85% and increase yield by a significant margin. This review addresses ecological, evolutionary, and operating components of microbial metabolite application towards the realization of sustainability in biological suppression of persistent BB and also indicates where gaps in research are needed to further the development of next-generation biological control methods for the suppression of BB.

Keywords: Bacterial blight, *Xanthomonas oryzae* pv. *oryzae*, beneficial bacteria, quorum sensing, rice microbiome.

Introduction

Rice (*Oryza sativa* L.) is a staple crop for more than half of the population of the world. One of its most prominent bacterial diseases is bacterial blight (BB), caused by *Xanthomonas oryzae* pv. *oryzae* (Xoo), a very destructive disease especially in irrigated ecosystems of Asia and Africa (Niño-Liu *et al*., 2006; Mansfield *et al*., 2012). BB is a disease that manifests chlorotic lesions along leaf veins, causing drastic losses in yield even under favourable environmental conditions (Mishra *et al*., 2013).

Host resistance genes (Xa alleles) and chemical bactericides, which are conventional control methods of BB, have declined in effectiveness with time due to the evolution of the pathogen and other environmental aspects. An advantageous option is developed in beneficial bacteria, which reduces the incidence of BB through metabolite-mediated virulence interference and host immune priming (Compant *et al*., 2019; Trivedi *et al*., 2020).

Historically, the management of bacterial blight has relied heavily on the deployment of resistant rice varieties and the application of chemical bactericides. While host plant resistanceis is considered an environmentally sound approach, its effectiveness is often short-lived due to the rapid emergence of new virulent races of Xoo capable of overcoming resistance genes (Jiang et al., 2026; Tiwari et al., 2025). This evolutionary arms race between host resistance and pathogen virulence has necessitated continuous breeding efforts that are both time-consuming and resource intensive. Also, chemical control measures, although sometimes effective in reducing disease severity, are associated with several drawbacks, including environmental contamination, disruption of beneficial development of chemical resistance in pathogen populations (Sundaram et al., 2014). These challenges have driven the search for alternative, sustainable, and economically sound approaches to disease management.

In recent years, there has been a paradigm shift towards the utilization of beneficial microorganisms, particularly plant growth-promoting rhizobacteria (PGPR), as biological control agents in crop production systems (Andrade et al., 2023; Al Raish et al., 2025). PGPR inhabits the rhizosphere, and in some cases the endosphere, where they establish complex interactions with plant roots. These bacteria confer multiple benefits to the host plant, including enhanced nutrient acquisition, modulation of phytohormone levels, and improved tolerance to abiotic stresses. Significantly PGPR also play a role in the suppression of plant pathogens through a variety of direct and indirect mechanisms (Yang et al., 2024; Al Raish et al., 2025). One of the most critical aspects of their biocontrol potential lies in their ability to produce a diverse repertoire of secondary metabolites with potent biological activities.

The review focuses on the mechanistic insights of beneficial bacterial metabolites in rice BB inhibition and includes field and greenhouse results that reflect feasible efficacy.

Molecular Basis of Xoo Virulence

Type III Secretion System (T3SS)

The T3SS is a secretory platform found in most bacteria, which is pertinent to the current study. T3SS is prerequisite to Xoo pathogenicity, as it acts as a molecular syringe injecting effector proteins into the host cells (Mansfield *et al*., 2012). Destruction of the hrp gene cluster abolishes pathogenicity, which demonstrates T3SS as an optimal virulence attenuation target.

Host Susceptibility and TAL Effectors

Transcription activator-like (TAL) effectors control transcription in the host, such as the expression of sweet sugar transporter genes that release nutrients to the apoplast (White and Yang, 2009; Hutin *et al*., 2015).

Iron Acquisition

Xoo relies on siderophores and TonB-dependent systems of iron uptake managed by ferric uptake regulator (Fur) proteins (Mansfield *et al*., 2012). Competing beneficial bacteria may induce iron restriction, making the pathogen inactive in its metabolism and virulence (Trivedi *et al.*, 2020).

DSF Quorum Sensing

Quorum sensing is mediated by DSF to regulate the production of EPS, biofilm formation and virulence factors expression (He, & Wu,, 2010). The disruption of DSF signalling is a major large-scale virulence modulation strategy.

Extracellular Polysaccharides (EPS)

EPS aids in the development of biofilms and xylem colonization, protecting Xoo from host defenses and other environmental stressors (Mansfield *et al.*, 2012).

Advantageous Bacterial Metabolites and Suppressive Mechanisms

Lipopeptides

Surfactin, iturin, and fengycin lipopeptides produced by *Bacillus* spp. regulate pathogen virulence and host immunity (Ongena & Jacques, 2008). The expression of T3SS genes is inhibited with surfactin action, resulting in induced systemic resistance (ISR) in rice seedlings (Jin *et al*., 2020; Pieterse *et al*., 2014).

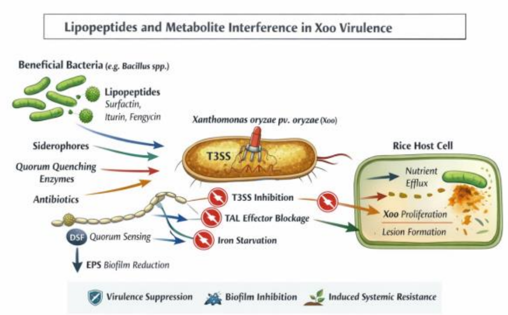

Figure 1. *Mechanisms of lipopeptides and other metabolites in interfering with Xoo virulence factors.*

Competition between Siderophores and Iron

The high affinity of siderophores to bind iron restricts accessibility to Xoo and reduces the expression of virulence genes (Trivedi *et al*., 2020). Field tests done with siderophore-producing strains indicated disease suppression rates up to 60% (Naveed *et al*., 2025).

Quorum Quenching

Some strains of *Bacillus* and *Pseudomonas* secrete DSF-degrading enzymes that impair Xoo quorum sensing, which limits EPS production, biofilm development, and expression of virulence factors (He & Wu,, 2010; Compant *et al*., 2019).

Volatile Organic Compounds (VOCs)

Volatile organic compounds (VOCs) are volatile substances found in the atmosphere which led to high levels of air pollution. Bacterial VOCs, such as acetoin and 2, 3-butanediol trigger systemic resistance and activate the jasmonic acid and ethylene pathways (Ryu *et al*., 2004; Pieterse *et al*., 2014).

Antibiotics and Secondary Metabolites

Phenazines, DAPG, and pyrrolnitrin inhibit the growth of Xoo and suppress the expression of virulence genes (Compant *et al*., 2019; Ali *et al*., 2016).

Biofilm Interference

Competition also affects colonization by beneficial bacteria and alters the xylem microenvironment, thereby preventing Xoo biofilm formation (Trivedi *et al*., 2020).

Greenhouse and Field Trials Evidence

Bacillus velezensis BTR11

As much as 85% reduction in incidence of BB was found with the use of foliar sprays and seedling treatment, with yield increase improved by an average of 12% in field experiments (Naveed *et al*., 2025).

Bacillus cabrialesii FA26 and B. atrophaeus FA12

Greenhouse experiments have shown reduced lesions up to 55-60%, with enhanced growth of seedlings (Wu *et al*., 2023).

Rhizosphere and Endophytic Consortia

The existence of Consortia of rice-associated rhizobacteria reduced the incidence of BB by 40-68%, as well as increasing yield parameters conducted under field experiments (Zhang *et al*., 2025).

Table 1 Placeholder: Comparative overview of the efficacy of beneficial bacterial strains against BB under greenhouse and field conditions.

Bacterial Strain	**Metabolites**	**Application Method**	**BLB Disease Reduction (%)**	**Yield Increase (%)**	**Reference**
Bacillus velezensis BTR11	Lipopeptides, siderophores	Seedling & foliar spray	85	12	Naveed et al., 2025
Bacillus atrophaeus FA12	Fengycin, surfactin	Foliar spray	55	8	Wu et al., 2023
Bacillus cabrialesii FA26	Fengycin, surfactin	Foliar spray	58	7	Wu et al., 2023
Rhizosphere consortia	Lipopeptides, siderophores, VOCs	Soil inoculation	40–68	10–18	Zhang et al., 2025

Integrative Mechanistic Framework

- Virulence interference at the metabolite level: Lipopeptides and siderophores, as well as antibiotics and quorum quenchers disrupt T3SS, TAL effectors, EPS and DSF.

- Consortia stability: Engineered microbial communities enhance

- Host immune priming: Lipopeptides and VOCs activate ISR.
- Resource competition inhibiting colonization: Biofilms and siderophores reduce colonization by the pathogen.

metabolite redundancy and field resilience.

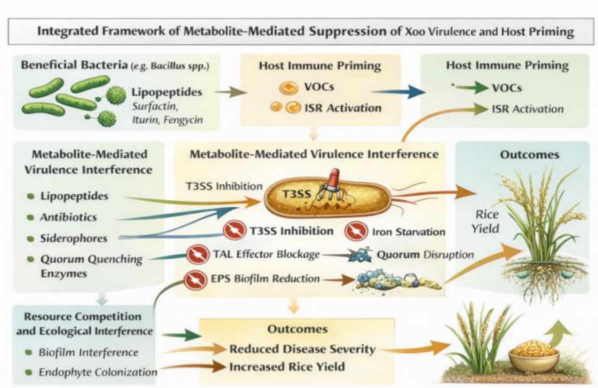

Figure 2. Integrated framework illustrating how beneficial bacterial metabolites suppress Xoo virulence and prime the host immune response, leading to reduced disease severity and enhanced rice yield.

Gaps in Knowledge and Future Directions

- There is need to further examine molecular interactions between TAL effectors and metabolite apps.

- Optimization in dosage, formulation and delivery for field applications is necessary.
- Synergistic effects could be achieved by integration with host resistance (Xa alleles).
- Strain selection process may be improved with help from metabolomics, particularly to enhance the efficiency of suppression, yielding benefits.

Conclusions

Multi-layered virulence modulation with beneficial bacteria is characterized by interference with metabolites, quorum quenching, induction of ISR, and competition, to suppress the expression of rice BB. Their practical efficacy has been proven in greenhouse and field tests, supporting the concept of microbial metabolites being a long-term and cost-efficient strategy for BB control.

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ADOPTION OF PLANT GROWTH-PROMOTING RHIZOBACTERIA FOR SUSTAINABLE CROP PRODUCTION: A REVIEW

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ABSTRACT

New methods that boost crop productivity while reducing environmental damage from overuse of chemicals are necessary for sustainable agricultural production. Plant Growth-Promoting Rhizobacteria (PGPR), a diverse group of beneficial soil microorganisms that flourish on plant roots and encourage plant growth through a range of mechanisms, is one of the biological substitutes that has gained popularity recently. These bacteria enhance the performance of plants by assisting in the acquisition of nutrients, the production of phytohormones, and improving their tolerance to biotic and abiotic stress. A number of well-studied genera, including *Rhizobium*, *Azospirillum*, *Pseudomonas*, and *Bacillus*, have demonstrated great potential in improving soil fertility, increasing the efficiency of nutrient utilization, and inhibiting plant pathogens. PGPR can be used to improve sustainable agriculture through a number of mechanisms, including stimulating nitrogen bio-fixation, solubilizing insoluble phosphates, synthesizing siderophores, which increase the availability of iron. By controlling plant hormones and promoting root development, PGPR helps crops withstand a variety of environmental challenges, including drought, salinity, and severe temperatures, in addition to its contributions to plant nutrition and disease management. Despite its potential uses, PGPR's widespread worldwide adoption has been hampered by inconsistent field performance, formulation instability, and farmer ignorance. However, new developments in microbial ecology, biotechnology, and formulation methods contribute to improving the reliability and commercial attractiveness of PGPR inoculants. This essay examines the ways in which Plant Growth-Promoting Rhizobacteria (PGPR) enhance crop yield, their application in sustainable farming systems, their difficulties, and their prospects for widespread usage in the future. A viable route toward robust and environmentally friendly crop production systems is the introduction and integration of PGPR into modern agricultural operations.

Key words: *Azospirillum*; Environmentally friendly; Plant hormones; Microbial ecology; *Rhizobium*; Siderophores.

Introduction

The globe currently faces two challenges: producing enough food to feed a population that is growing at an accelerated rate while also reducing the effects of environmental degradation brought on by the use of intensive farming methods. There will be more than 9 billion people on the planet by 2050, which will place tremendous pressure on agricultural systems to increase production (Food and Agriculture Organization [FAO], 2017). In the past, methods for increasing output have primarily relied on the widespread application of chemical fertilizers. Although these inputs have significantly increased agricultural yields, excessive use of them has resulted in soil erosion, nutrient imbalance, groundwater contamination, biodiversity loss, and greenhouse gas emissions (Tilman et al., 2002; Foley et al., 2011). Since then, there has been a demand for sustainable agricultural techniques and policies that maintain productivity without unduly upsetting the natural balance.

The long-term health of the soil, environmental security, and resource efficiency are the main concerns of sustainable agriculture. In this regard, soil microorganisms, particularly those in the rhizosphere are essential to maintaining the fertility and productivity of the soil. The rhizosphere, a layer of soil that is primarily impacted by plant root exudates and interacts directly with these roots, is home to complex microbial ecosystems (Philippot, L., Raaijmakers, J. M., Lemanceau, P., & van der Putten, W. H. (2013). Among these microbes, Plant Growth Promoting Rhizobacteria (PGPR) have emerged as crucial biological agents that, through a variety of processes, can enhance plant development and resilience to a range of stresses. The term PGPR was first coined by Kloepper and Schroth (1978) to characterize beneficial root-colonizing bacteria that encourage plant growth. Since then, a great deal of research has demonstrated that PGPR action is mediated through both direct and indirect channels, ultimately assisting in pathogenic suppression, balancing phytohormones, and improving the nutritional status of plants (Vessey, 2003; Lugtenberg & Kamilova, 2009). The concept of plant holobiont, which explains that plants and their microbiota function as a single biological system, is valid, as evidenced by the increasing sophistication of molecular biology and omics technologies (Berendsen et al., 2012).

PGPR directly promotes plant growth by ... solubilization, potassium mobilization, siderophore synthesis, and phytohormone synthesis. Nitrogen-fixing bacteria increase a plant's nitrogen content by converting atmospheric nitrogen into ammonia (Glick, 2012). Organic acids and phosphatases secreted by phosphate-solubilizing bacteria transform insoluble phosphates into forms that plants can absorb (Rodriguez and Fraga, 1999). Gibberellins, cytokinins, and indole-3-acetic acid (IAA), which alter root architecture and boost nutrient uptake, are also produced by several PGPR (Spaepen et al., 2007). Furthermore, microorganisms that make ACC deaminase control ethylene levels in plants, preventing growth inhibition brought on by stress (Glick et al., 2007).

PGPR improves biological control of plant diseases in addition to nutritional supplementation. Antibiosis, lytic enzyme production, competition for nutrients and ecological niches, and systemic resistance (ISR) in host plants are some of the strategies they employ to combat infections (Compant et al., 2005; Pieterse et al., 2014). ISR entails priming plant defence mechanisms to enable plants to react to pathogen attacks more swiftly and efficiently. PGPR's biocontrol capacity reduces the need for artificial pesticides and supports eco-friendly crop protection techniques. Climate change has made abiotic stressors including drought, salinity, harsh temperatures, and heavy metal toxicity worse, which significantly reduces crop output. By building up osmolytes, triggering antioxidant enzymes, enhancing root shape, and controlling hormones, PGPR helps plants become more resilient to various challenges (Yang et al., 2009; Vurukonda et al., 2016). In areas like sub-Saharan Africa, where smallholder farmers are dealing with increased climatic changes, mitigating these stress-effects positions PGPRs as a contributor to climate-smart agriculture.

The functional variety of bacteria and signalling relationship are better understood thanks to recent advances in metagenomics, transcriptomics, and metabolomics (Mendes et al., 2013). These technologies are making it possible to develop microbial consortia and next-generation biofertilizers that are suited to specific crop and agroecological circumstances. Despite encouraging outcomes in labs and greenhouses, large-scale field application of PGPR is still uneven. Some of the barriers to the broad application of PGPRs include variations in soil type, environmental conditions, microbiological viability, formulation stability, and regulatory requirements (Malusa et al., 2012).

Growing environmental consciousness, declining soil fertility, and the need for sustainable intensification have made PGPR a feasible biological substitute for overuse of pesticides. In order to advance sustainable agriculture systems, PGPRs are crucial. They improve plant health, discourage infections, raise plant tolerance to abiotic stresses, and improve nutrient use efficiency. This study examines the mechanisms, applications, constraints, and future prospects of rhizobacteria that promote plant development in sustainable agriculture.

Plant Growth Promotion by Rhizobacteria

Through a variety of physiological and biochemical processes that occur in the rhizosphere, plant growth-promoting rhizobacteria (PGPR) enhance plant development and productivity. These mechanisms can be broadly classified as either direct or indirect processes, depending on whether they improve plant growth and nutrition or shield the plant from environmental stressors and pathogens (Glick, 2012). PGPR plays a significant role in improving soil fertility, nutrient availability, and plant resilience in sustainable agricultural systems because to

Biological Nitrogen Fixation.

Although atmospheric nitrogen (N_2) cannot be directly utilized by plants, nitrogen is an essential ingredient that they need. Through biological nitrogen fixation, certain PGPRs are able to fix atmospheric nitrogen and turn it into ammonia. The enzyme nitrogenase aids in this process by assisting bacteria in transforming inert nitrogen gas into forms that plants can use (Vessey, 2003).

Among the bacterial genera recognized for their capacity to fix nitrogen are Rhizobium, Azotobacter, and Azospirillum. Legumes and Rhizobium species are particularly notable for symbiotic nitrogen fixation, in which the plant provides carbon compounds to the bacteria in return for fixed nitrogen, while the bacteria live in specialized root nodules of the plant. Non-symbiotic nitrogen-fixing bacteria like Azotobacter also contribute to soil nitrogen enrichment in the majority of agricultural systems (Vessey, 2003). By lowering the need for artificial nitrogen fertilizers and reducing environmental contamination brought on by overuse of fertilizers, these microorganisms contribute to lower production costs.

Phosphate Solubilization

Phosphorus is another crucial macronutrient required for plant metabolism, particularly for energy transmission, nucleic acid synthesis, and membrane production. Phosphorus is present in large amounts in many soils, but a large portion of it is bound in insoluble forms that are unavailable to plants. By transforming these insoluble forms into soluble orthophosphates that plants can absorb, PGPR increases the availability of phosphorus. In order to dissolve mineral phosphates and decrease the pH of the surrounding soil, phosphate-solubilizing bacteria secrete organic acids like citric acid and gluconic acid (Hilda &

Reinaldo, 1999). It is commonly known that Enterobacter, and Pseudomonas are efficient phosphate solubilizers. By boosting phosphorus levels in the rhizosphere, these bacteria improve plant growth and nutrient uptake.

Synthesis of Phytohormones

Through the manufacture of plant growth regulators like auxin, cytokinins, and gibberellins, a number of PGPR control how plants develop. Rhizobacteria generate indole-3-acetic acid (IAA), the auxin that has been studied the most. By encouraging root elongation, lateral root development, and root hair growth, bacterial IAA plays a significant role in changing root structure and improving the plant's ability to absorb water and nutrients from the soil (Sofie Spaepen et al., 2007).

Bacterial hormones help plants grow and produce better root systems, especially when nutrients are few. Gibberellins and cytokinins are two other hormones released by PGPRs that support shoot development, cell division, and overall plant vigour.

Siderophore Production

Majority of plant metabolic processes, including the synthesis of chlorophyll and enzyme activity, require iron, a crucial micronutrient. However, iron is present in insoluble forms in the majority of soils. As a result, in these circumstances, plants cannot obtain this nutrient (Neilands, 1995; Ahmed & Holstrom, 2014). By creating siderophores, which are low-molecular-weight substances that bind firmly to iron and promote its absorption, PGPRs assist get around this. In order to make iron available to plants, these siderophores chelate ferric ions (Fe^{3+}) from the soil environment and carry them to the bacterial cells. By lowering the amount of iron needed for the pathogen's growth, siderophores can enhance iron nutrition and prevent the growth of plant pathogens (Ben & Faina, producing bacteria in biodiversity-based agricultural production systems is indicated by this dual role.

ACC Deaminase Activity

A phytohormone called ethylene is involved in a number of physiological processes, including stress reactions. High ethylene concentrations in plants are frequently caused by unfavourable environmental factors including dryness, salinity, or disease infection, which can impede root development and reduce plant output (Saleem, 2007; Singh et al., 2015; Hewedy, et al., 2026). The enzyme 1-aminocyclopropane-1-carboxylate (ACC) deaminase, which degrades ACC, the direct precursor of ethylene in plants, is present in several PGPRs. According to Glick et al. (2007), these bacteria therefore aid in lowering ethylene levels in plants, enabling them to grow normally under stressful conditions. The procedure has been acknowledged as a key mechanism for enhancing plant resistance to abiotic stress conditions, particularly in settings that are prone to salt or drought.

Induced Systemic Resistance

Through a process called induced systemic resistance (ISR), PGPR can improve plant defence systems in addition to enhancing plant nutrition. In this mechanism, the plant's innate immune system is stimulated by helpful rhizobacteria, enabling it to respond to pathogen attacks more successfully. Unlike direct antibacterial activity, ISR triggers plant defence pathways, allowing defence mechanisms to respond to pathogens more quickly and forcefully (Pieterse et al., 2014; Van et al., 2008; Kloepper et al., 2004). Plant hormones like ethylene and jasmonic acid have been found to affect signalling pathways involved in ISR, which is mediated by PGPR (Cornéet al., 2014).

These enhanced defensive capabilities reduce the incidence and severity of diseases brought on by bacterial, viral, and fungal pathogens.

Role of Plant Growth-Promoting Rhizobacteria in Sustainable Crop Production Systems

It is anticipated that sustainable crop production will minimize negative environmental effects, protect natural resources, and guarantee high agricultural yield. The hunt for environmentally friendly agricultural inputs has increased over the past few decades due to worries about low soil fertility, soil deterioration, and environmental contamination brought on by excessive use of chemical pesticides and fertilizers. Because they can increase agricultural productivity by enhancing natural biological processes in the rhizosphere, plant growth-promoting rhizobacteria (PGPR) are another potential biological alternative. PGPR has made significant contributions to sustainable crop production systems, such as improving nutrient availability, boosting plant growth, and shielding plants from disease.

By colonizing plant roots and developing complex connections with their host plants, these helpful microbes eventually improve the production and performance of these plants. They are now an important component of the agricultural system and a means of reducing the demand for artificial agrochemicals to sustain and raise crop production.

Improvement of Soil Fertility

Improving soil fertility is one of PGPR's main contributions to sustainable crop production. The decomposition of organic matter, the cycling of nutrients, and the maintenance of soil structure all depend on soil microorganisms. By releasing essential nutrients like potassium, phosphate, and nitrogen into the rhizosphere, PGPRs also actively participate in these activities (Vessey, J. K., 2003; Lugtenberg, B., & Kamilova, F., 2009; Glick, B. R., 2012; Bhattacharyya, P. N., & Jha, D. K., 2012).

Rhizobium, *Azospirillum*, and *Azotobacter* species are examples of nitrogen-fixing bacteria that convert atmospheric nitrogen into forms that plants can absorb. This bio-fixation mechanism plays a major role in fixing nitrogen in the soil, which is particularly crucial for nitrogen availability in the soil for farming systems based on legumes (Vessey, 2003). Additionally, organic acids secreted by phosphate-solubilizing bacteria convert insoluble phosphorus molecules into soluble ones, increasing the availability of phosphorus for plants (Rodriguez & Fraga, 1999). PGPRs minimize the usage of synthetic fertilizers and maximize the use of nutrients through these processes.

Improvement in Crop Yield and Productivity

Numerous studies have demonstrated that PGPR crop inoculation may significantly boost plant growth and output ((Khalid et al., 2004; Abd El-Mageed et al., 2022). The capacity of PGPR to generate phytohormones that control plant growth and development, such as auxins, cytokinins, and gibberellins, is primarily responsible for these effects. By enhancing root architecture and biomass accumulation, these hormones support plant growth and biomass. Research has also shown that PGPR inoculation can increase the yields of a variety of crop types, including vegetables, legumes, cereals, and horticultural crops. (Vessey, 2003; Lucy et al., 2004

. Bhattacharyya & Jha, 2012). For instance, it has been extensively documented that bacterial species belonging to the genera Pseudomonas and Bacillus promote plant growth through a variety of mechanisms, such as hormone synthesis, nutrient solubilization, and plant pathogen control

(Lugtenberg and agricultural viability and improved crop output are the overall results of these procedures.

Reduction in Chemical Fertiliser Dependency

Chemical fertilizers have been a major component of modern agriculture, ensuring excellent crop yields. However, the usage of these inputs has led to a number of environmental problems, including soil acidification, nitrogen imbalance, and water body contamination from chemical runoff. Through the natural availability and uptake of nutrients, PGPRs offer a more sustainable approach.

Without lowering crop performance, PGPR-based biofertilizers can partially replace chemical fertilizers. By improving the biological fixation of nitrogen, solubilization of phosphorus, and mobilization of nutrients, these bacteria both positively maintain soil fertility and decrease the need for fertilizers. Therefore, including PGPRs into different cropping systems contributes to agriculture's increased environmental sustainability (Glick, 2012).

Biological Suppression of Plant Diseases

The ability of PGPR to control plant diseases is another significant contribution to sustainable production (Compant et al., 2005; Lugtenberg & Kamilova, 2009; Glick, 2012). To inhibit the growth of harmful microbes in the rhizosphere, a number of rhizobacteria release siderophores, enzymes, and antimicrobial compounds. Furthermore, certain PGPR strains enable plants develop induced systemic resistance, which improves their ability to fend off pathogen attacks (Kloepper et al., 2004; Compant et al., 2005; Lugtenberg & Kamilova, 2009).

In addition to being an eco-friendly substitute for chemical pesticides, this biological control method reduces the esistance developing as a result of frequent pesticide usage. According to research, PGPR has been effective in controlling a number of soil-borne diseases that target crops like vegetables, rice, wheat, and corn (Compant et al., 2005). Thus, it may be concluded that PGPR is crucial for integrated disease management programs for sustainable agricultural production systems.

Contribution to Soil Health and Microbial Diversity

Sustainable crop production also requires biologically active and healthy soils. The improvement of beneficial microbial relationships in the soil's rhizosphere is linked to PGPR. Their actions create a more stable and balanced soil ecology by boosting the diversity of bacteria and encouraging the growth of other beneficial microorganisms (Barea et al., 2005; Berendsen et al., 2012; Bhattacharyya & Jha, 2012).

Nutrient cycling, enhanced plant growth, and resistance to diseases and environmental stressors are all enhanced by a diverse rhizosphere microbiome. Thus, the presence of beneficial rhizobacteria enhances both the immediate productivity of crops and the long-term sustainability of agricultural soils for future production methods (Philippot et al., 2013).

Role of Plant Growth-Promoting Rhizobacteria in Abiotic Stress Tolerance

Abiotic stress, such as drought, salinity, severe temperatures, and heavy metal contamination, are some of the biggest obstacles to global agricultural productivity. Plant physiological processes are disrupted by these environmental constraints, which reduce nutrient uptake and ultimately result in significant production losses. In light of current climate change and growing concerns about environmental degradation, improving plant tolerance to abiotic stressors has been identified as one of the key co

Through a variety of physiological and biochemical routes, plant growth-promoting rhizobacteria (PGPR) have emerged as a promising biological agent that could be exploited to boost plant resilience to unfavourable environmental variables (Glick, 2012). By colonizing the rhizosphere and establishing advantageous relationships with plant roots, PGPR help plants better withstand environmental stressors. By controlling phytohormone levels, boosting nutrient uptake, strengthening antioxidant defence systems, and improving root architecture, these microbes affect how plants react to stress (Yang et al., 2009; Glick, 2014; Vurukonda et al., 2016). PGPR contributes significantly to the development of cropping systems that can withstand stress through these mechanisms.

Drought Stress Tolerance

In most parts of the world, one of the abiotic factors that seriously affects crop productivity is water scarcity. By decreasing water availability, photosynthesis, and nutrient transfer in plant tissues, drought conditions prevent plants from growing. By increasing root development and water uptake efficiency, a number of PGPR species have been demonstrated to improve plant resistance to drought (Vurukonda et al., 2016; Ngumbi & Kloepper, 2016; Timmusk et al., 2014). By producing phytohormones, particularly auxins, rhizobacteria such as Azospirillum, Bacillus, and Pseudomonas stimulate the growth of plant roots (Spaepen et al., 2007; Dobbelaere et al., 2003; Glick, 2012). During the dry seasons, plants with better established root systems would be able to reach water more effectively and seek larger soil masses (Vurukonda et al., 2016). Additionally, certain PGPR generate exopolysaccharides that improve soil aggregation and water retention in the rhizosphere, creating a more favorable microenvironment for plant growth during

et al., 2014; Vurukonda et al., 2016).

Salinity Stress Mitigation

Soil salinity is another major problem that affects agricultural productivity, particularly in dry and semi-arid regions. Osmotic stress, ion toxicity, and nutritional imbalance in plants can happen when the amount of soluble salts in the soil is high. By improving plants' physiological adaptation to salt tolerance, PGPR can help lessen the negative effects of salinity (Egamberdieva et al., 2017; Etesami & Beattie, 2018; Vurukonda et al., 2016).

Many rhizobacteria increase salt tolerance by controlling the osmotic balance and plant hormone levels in plant cells. Additionally, some PGPR cause compatible solutes including proline and glycine betaine to accumulate, maintaining cell integrity in saline environments (Jinliang et al., 2009). Furthermore, bacterial inoculation may enhance the uptake of nutrients and reduce the harmful effects of sodium ions in plant tissues.

Regulation of Stress Ethylene Through ACC Deaminase

The hormone ethylene, which inhibits root elongation and overall plant growth, is frequently secreted in large quantities by plants under stressful climatic conditions. However, certain PGPR have the enzyme 1-aminocyclopropane-1-carboxylate (ACC) deaminase, which degrades ACC, a direct precursor to ethylene in plants. According to Glick et al. (2007), these bacteria aid in lowering ethylene levels in plants, enabling normal growth even under stressful circumstances. This activity is thought to be one of the most important ways that PGPR increases plants' resistance to a wide range of abiotic factors, including salinity, drought, flooding, and heavy metal toxicity.

Enhancement of Antioxidant Defence

Under adverse environmental conditions, plant cells typically create excessive amounts of reactive oxygen species (ROS). These substances may cause oxidative stress by harming proteins, lipids, and nucleic acids, among other cellular constituents. It has been discovered that PGPR activates plant antioxidant systems, which neutralize ROS and shield plant tissues from oxidative damage (Kohler et al., 2009; Vurukonda et al., 2016; Egamberdieva et al., 2017).

Additionally, it has been demonstrated that these rhizobacteria activate antioxidant enzymes including peroxidase, catalase, and superoxide dismutase, which are essential for preserving the cell's redox balance. PGPR can increase plant survival and yield under unfavourable conditions by stimulating these defence systems (Vurukonda et al., 2016; Egamberdieva et al., 2017; Timmusk et al., 2014).

Heavy Metal Stress Tolerance

Agricultural productivity and food security are threatened by the presence of heavy metals in the soil, such as arsenic, cadmium, and lead Alloway, 2013; Shahid et al., 2017; Tóth et al., 2016). By immobilizing the harmful metals in the soil, producing metal-binding compounds, or accelerating plant detoxification processes, certain PGPR species can help plants withstand the effects of these heavy metals (Rajkumar et al., 2012; Ma et al., 2016; Glick, 2010). By increasing plant biomass and encouraging the uptake or stabilization of heavy metals in contaminated soils, these bacteria can also enhance the phytoremediation process. As a result, there is increasing interest in investigating the application of PGPR as an eco-friendly method for cleaning up contaminated agricultural areas (Rajkumar et al., 2012; Ma et al., 2016; Glick, 2010).

PGPR in Biological Control of Plant

Plant disease-causing fungi, bacteria, nematodes, and viruses pose a serious threat to world agricultural output and food security. Traditionally, synthetic insecticides and fungicides have been used to manage these infections. However, the misuse of chemical control techniques has resulted in a number of issues, including disease resistance, environmental contamination, and adverse impacts on non-target species. In order to manage illnesses in sustainable agricultural systems, plant growth-promoting rhizobacteria (PGPR) have attracted a lot of attention lately as an alternative to the usage of dangerous agents (Compant et al., 2005; Lugtenberg and Kamilova, 2009).

Through a number of direct and indirect antagonistic mechanisms that limit the proliferation and activity of phytopathogens in the rhizosphere, PGPR controls plant diseases. One of the most often described processes is the synthesis of antimicrobial compounds, including lytic enzymes, siderophores, hydrogen cyanide (HCN), and antibiotics (Compant et al., 2005; Lugtenberg & Kamilova, 2009; Glick, 2012). Antibiotics such phenazines, pyrrolnitrin, and 2,4-diacetylphloroglucinol, which stop the growth of numerous soil-borne diseases, are particularly known to be produced by the genera Pseudomonas, Bacillus, and Streptomyces (Haas et al., 2005; Weller, 2007). These bioactive compounds reduce the incidence of disease by interfering with cell membranes, pathogen metabolism, or vital enzyme functioning.

Another important way that PGPR prevents illness is through competition for resources and ecological niches in the rhizosphere. Microorganisms in the rhizosphere battle fiercely for limited resources like iron and carbon sources. In the same setting, PGPR can successfully establish itself on plant roots and compete with harmful microbes. Indicatively, many PGPR create high-affinity siderophores, which bind iron in the soil habitat and prevent disease-causing bacteria from proliferating (Kloepper et al., 2004; Lugtenberg & Kamilova, 2009).

Another method of biological control by PGPR is the synthesis of lytic enzymes that can degrade pathogen cell walls. Many enzymes, including cellulases, glucanases, proteases, and chitinases, can break down the structural components of fungal cell walls, causing the pathogens to lyse. Fungal diseases like Fusarium, Rhizoctonia, and Sclerotium species are particularly potent against this enzyme action and cause significant crop losses worldwide (Glick, 2012; Bhattacharyya and Jha, 2012).

The induction of systemic resistance in plants, sometimes referred to as induced systemic resistance (ISR), is one of the most significant indirect processes employed by PGPR. During this process, certain rhizobacteria trigger the plant's natural defence system, enabling it to respond to pathogen attacks considerably more quickly and efficiently. By stimulating the plant's immune system through a signalling cascade involving phytohormones like ethylene and jasmonic acid, ISR does not directly cause the pathogens to die. As a result, PGPR-colonized plants typically exhibit strong resistance to a variety of diseases, including bacteria, fungi, and viruses (Pieterse et al., 2014; Van Loon et al., 1998).

PGPR has been used to biologically manage several economically significant plant diseases. For instance, *Bacillus subtilis* has been widely used to prevent soil-borne pathogens that attack crops like tomato, cucumber, and rice, while *Pseudomonas fluorescens* has been demonstrated to diminish take-all disease of wheat, caused by *Gaeumannomyces graminis* (Weller, 2007; Compant et al., 2005). Similarly, several PGPR strains have been shown to lessen the severity of Rhizoctonia, Phytophthora, and Fusarium infections in various crops (Compant et al., 2005; Lugtenberg & Kamilova, 2009; Vurukonda et al., 2016).

When opposed to conventional chemical-based control methods, the use of PGPR in crop management approaches offers a number of advantages. These beneficial microbes improve plant development, nutrient uptake, and soil health in addition to suppressing plant diseases. Thus, PGPR application is an important component of integrated disease management (IDM) and advances the broader goals of sustainable agriculture (Bhattacharyya & Jha, 2012).

Despite these promising benefits, PGPR's efficacy as a biological control agent may be impacted by field-specific environmental factors, such as soil type, microbial competition, and climate change. Therefore, more study is required to find stronger strains, improve formulation methods, and develop reliable delivery systems to boost PGPR's survival and effectiveness in agricultural soils (Lugtenberg and Kamilova, 2009; Pieterse et al., 2014).

In conclusion, the several mechanisms that these bacteria have employed, such as the synthesis of antibiotics, competition for resources, the release of lytic enzymes, and the creation of systemic plant resistance, validate the critical functions that PGPR plays in the control of plant diseases. Because of their adaptability, they can be used to improve environmentally friendly food production systems and reduce dependency on chemical pesticides.

Challenges Limiting the Field Application ofPlant Growth-Promoting Rhizobacteria (PGPR)

Growth-promoting rhizobacteria (PGPR) have enormous potential to increase crop yield and support sustainable agricultural systems, but their widespread use in the field has been limited. The beneficial effects of management have been demonstrated in numerous lab and greenhouse studies, but the behavior of these microbes in natural settings is not always predictable. This diversity is caused by a number of biological, environmental, and technological factors that limit the practical application and worldwide commercialization of PGPR-based bioinoculants.

One of the biggest obstacles to PGPR's efficacy in agricultural systems is poor rhizosphere development and survival. After the inoculation, newly introduced bacterial strains must contend with the soil's preexisting microbial communities. Because natural microorganisms frequently colonize plant roots, the introduced PGPR is typically outcompeted by them in terms of resources and ecological niches. However, effective colonization is still required since the good impact and beneficial benefits of PGPR can only be realized through the ability to be retained and sustained at sufficient population levels in the rhizosphere and around plant roots (Lugtenberg and Kamilova, 2009).

The effective use of PGPR is also impacted by variations in environmental conditions. Microbial activity and survival are greatly influenced by the type of soil, temperature, moisture content, pH, and nutrient availability. For example, harsh environmental conditions such as drought or excessive soil salt may make the implanted bacteria less viable and unable to stimulate plant development. Furthermore, depending on the crop species, soil properties, and local climate, some PGPR strains may perform differently (Bhattacharyya and Jha, 2012).

Inconsistent performance in the field as opposed to controlled settings is another drawback. In laboratory and greenhouse testing, the majority of PGPR strains show promising results; however, in open field tests, these results are not replicated. Complex interactions between plants, soil management techniques are typically the cause of such inconsistency. Farmers are less confident in the usage of PGPR-based products as a result of this variability (Compant et al., 2005).

Formulation and shelf-life issues are also present with PGPR bioinoculants. PGPR products must retain high bacterial viability throughout storage and transit in order to be economically viable. However, due to inadequate formulation techniques or poor storage conditions, the majority of microbial inoculants show low survival rates over time. To keep PGPR-based biofertilizers and biocontrol agents effective, formulation technologies and the development of stable carrier material are crucial (Malusá et al., 2012).

Additionally, strain compatibility and host specificity may have an impact on the effectiveness of PGPR inoculation. Different PGPR strains interact differently with different plant species or cultivars. One crop may benefit little or not at all from a bacterial strain that is good for its growth. Because of this specialization, it is important to carefully choose PGPR strains that are compatible with particular crops and agroecological conditions (Glick, 2012).

The lack of understanding among farmers and regulatory restrictions are further restrictive factors that hinder the worldwide implementation of PGPR-related technology. Most developing countries still lack a comprehensive regulatory framework for microbial inoculants, and even commercial biofertilizers may not always adhere to quality control standards. Because of this, goods on the market may have low microbe counts or inefficient strains, which reduces farmers' trust in biological remedies (Malusa et al., 2012).

Scientists are focusing increasingly on safe PGPR applications and techniques to improve PGPR performance in order to overcome these problems include creating multistrain microbial consortia, creating sophisticated carrier materials, and improving delivery systems that support bacterial survival and root colonization. Additionally, advances in microbial ecology and molecular biology are improving our knowledge of plant-microbe interactions, which can be utilized to create PGPR strains that are more robust and adaptable to different environmental conditions.

Future Prospects and Research Directions of PGPR in Sustainable Agriculture

The desire to concentrate on plant growth-promoting rhizobacteria (PGPR) as substitute fertilizers and pesticides in an attempt to be more sustainable has increased due to the growing worldwide demand for food and the developing environmental problems associated with intensive agricultural production. Even if there have been significant advancements in the beneficial impacts of PGPR on crop productivity, there are still a number of ways to improve the practical application of the microorganisms in modern agricultural production. Therefore, future research should focus on improving the effectiveness, reliability, and widespread use of PGPR-based technology.

One interesting line of study is the application of extremely advanced molecular and genomic techniques to better understand the nature of plant-microbe interactions in the rhizosphere. The most recent developments in proteomics, metabolomics, transcriptomics, and genomes have given researchers a wealth of information needed to examine the functional traits of beneficial microbes. Using these techniques, scientists can find genes that increase plant growth, provide drought resistance, and inhibit pathogens in PGPR. This information can be utilized to improve the selection of microbial inoculants with superior agronomic qualities ... terial strains (Backer et al., 2018; Vejan et al., 2016).

The creation of microbial consortia as opposed to single-strain inoculants is another crucial field for future study. Plants interact with complex communities of microorganisms rather than individual bacteria in natural soils. As a result, the benefits of mixing well-organized PGPR strains might be more consistent and dependable than those associated with using just one strain. Nutrient solubilization, phytohormone synthesis, disease control, and stress resistance are just a few of the activities that microbial consortia may do simultaneously, increasing plant productivity in a variety of settings (Berg et al., 2020).

For PGPR to be successfully commercialized,technological advancements in formulation and delivery systems are crucial. The most current bioinoculants are characterized by a number of limitations, including a short shelf life, a decline in microbial viability during storage, and an inability to endure field application. The creation of better carrier materials, encapsulating techniques, and controlled-release formulations that would enhance microbial stability and enable efficient colonization of plant roots should be the focus of future research. Some of the technologies being employed to improve the persistence and effectiveness of PGPR in soils include polymer-based encapsulation, biochar-encapsulation, and nano-formulations (Malusa et al., 2012; Bashan et al., 2014).

Combining PGPR with other sustainable farming practices, like organic farming, conservation farming, and integrated nutrient management systems, is another field of study. When used in conjunction with PGPR, the addition of organic amendments, compost, or diluted fertilizer may increase soil fertility and lower environmental pollution. The development of climate-resilient agricult can maintain productivity without contributing to soil degradation will greatly benefit from the combination of these tactics (Bhattacharyya & Jha, 2012).

To create PGPR strains that are specifically developed to match different agro-ecological situations, more research is also required. The efficacy of microbial inoculants can be impacted by a variety of regional environmental conditions, including cropping methods, soil composition, and climate. Therefore, in selective agricultural settings, the isolation and characterization of native PGPR strains from local soils may increase host plant adaptability and boost the effectiveness of bioinoculant technologies (Compant et al., 2005).

Microbial engineering and biotechnology also provide a lot of promise for enhancing PGPR's advantageous traits. Through genetic engineering and synthetic biology, scientists may be able to create bacteria with enhanced functions, such as phosphate solubilization, nitrogen fixation, and the synthesis of bioactive chemicals that suppress plant diseases. However, in order to preserve environmental safety, the production and use of genetically modified microbes should be accompanied by careful risk assessment and governmental oversight (Backer et al., 2018).

In order to encourage the use of PGPR-based technologies, it will also be necessary to increase farmer knowledge, provide training, and enhance extension services. The majority of farmers are still unaware of the benefits and proper ways to apply microbial biofertilizers and biocontrol agents. To translate scientific discoveries into workable solutions that can help farmers and promote agricultural sustainability, researchers, agricultural extension organizations, legislators, and the business community must work together more closely.

In order to achieve sustainable agriculture, plant growth-promoting rhizobacteria (PGPR) have become an essential biological agent. The application of PGPR guarantees higher crop yields and reduces the need for synthetic fertilizers and pesticides through increased nutrient levels, phytohormone production, disease suppression, and enhanced plant resilience to unfavourable environmental circumstances. These microbes are multifunctional in maintaining plant health and soil fertility, as evidenced by their processes of nitrogen fixation, phosphate solubilization, siderophore synthesis, ACC deaminase activity, and systemic resistance stimulation.

PGPR is a promising method for improving soil fertility, increasing crop output, and reducing the use of synthetic agrochemicals. The full potential of PGPR in sustainable agriculture will require more research on microbial ecology, formulation technology, multi-strain inoculants, and farmer-oriented applications.

Despite the fact that these benefits have been demonstrated, a variety of limitations prevent PGPR from being widely used in field settings. Environmental variability, competition from native soil bacteria, unpredictable performance, and limitations in formulation and delivery technology are some of these. In order to combat these issues, ongoing research based on agro-ecological contexts is required in the fields of strain selection, multi-strain consortia, enhanced formulation techniques, and locally-specific application strategies. Particularly in the areas of microbial genomics, biotechnology, synthetic biology, and integrated crop management systems, PGPR research has bright future prospects. More advancements in these areas, along with increased farmer awareness and effective extension services, can fully utilize PGPR's benefits in crop production in a sustainable way. In the end, incorporating

PGPR into contemporary farming sectors offers a way to achieve sustainable food security through high-yielding, ecologically friendly, and climate-sensitive food production.

In conclusion, there are still many barriers to PGPR implementation in big fields, despite the technology's encouraging potential to provide sustainable agriculture. In order to properly utilize PGPR in modern agricultural systems, issues with microbial survival, environmental variability, formulation technology, and farmer adoption must be resolved.

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