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Editorial message

Dear Readers and Contributors,

We are delighted to present Volume 3, Issue 2 of the Journal of Agriculture & Forestry Research (JAFR). We extend our heartfelt gratitude to the dedicated reviewers whose expertise and diligent evaluations have ensured the integrity and quality of this publication. Their constructive feedback and unwavering commitment are integral to maintaining the high standards of our journal.

We also express our sincere appreciation to the authors for their invaluable contributions. Their innovative research and insightful perspectives are the cornerstone of our journal's success.

Thank you for your continued support and dedication to advancing the field.

Sincerely,

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Journal of Agriculture & Forestry Research (JAFR)

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Research Article **Open access**

Effect of Ginger and Cloves Fortification on the Microbial, Proximate, Sensory and Bioactive Constituents of Pito

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ABSTRACT

Pito is a sorghum-based beverage widely consumed in Nigeria and some parts of Africa, but the quality of the beverage has not been well documented. This study therefore investigated the effect of fortification on the quality of fermented pito. Different samples of pito were prepared; 100% sorghum (control), 75% sorghum + 15% cloves + 10% ginger and 65% sorghum + 20% cloves + 15% ginger. The microbial, proximate, sensory and bioactive constituents of the pito samples were determined. Data was analyzed using ANOVA at $p < 0.05$. Highest bacterial, fungal and coliform counts were recorded in the100% sorghum pito. Among the isolates, *Saccharomyces cerevisiae* was the predominant with percentage occurrence ranging from 84.75 to 100% in 100% sorghum pito and 65% sorghum + 20% cloves +15% ginger fortified pito respectively. Highest fat, protein and fiber content was recorded in the pito produced with 75% sorghum + 15% cloves + 10% ginger. The tannin, alkaloids, flavonoids and phenol constituents of the 75% sorghum + 15% cloves + 10% ginger fortified pito are significantly higher ($p < 0.05$) than the rest of the pito samples. Moreover, the sensory scores with respect to colour, taste and overall acceptability of the 75% sorghum + 15% cloves + 10% ginger fortified pito was significantly higher ($p < 0.05$) than the rest of the pito samples. Fortifying sorghum with cloves and ginger at the right proportion during pito preparation will help in meeting the microbiological, nutritional, sensory quality and health needs of consumers.

Keywords: Beverages, Pito, *Saccharomyces cerevisiae*, Sorghum, *Syzygium*, *Zingiber officinale*

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INTRODUCTION

Sorghum beer (pito) is an alcoholic beverage usually produced from fermented sorghum. It is mainly produced in northern Ghana, parts of Nigeria, and other parts of West Africa. The beverage is produced on a small scale and household basis and can be served either warm or cold in calabash outside the producer's home, where benches are sometimes provided for the consumers (Zaukuu et al. 2016). Pito brewing is a vital source of income for low income earners in rural areas. In Nigeria, many women especially in rural areas are involved in small scale production of pito which has helped to alleviate poverty among the people. However, the production of pito for commercial purposes and its processing is highly prone to microbial contamination (Abimbola and Alagamba, 2020). Many microorganisms implicated in pito contamination may include bacteria such as *Escherichia coli*, *Salmonella* species, *Shigella* species, *Staphylococcus aureus* (Umaru et al. 2014) and fungi such as *Aspergillus flavus*, *Aspergillus niger,* and *Saccharomyces cerevisiae* (Clavijo et al. 2011).

According to Sefah-Dedeh et al. (1999), the production processes for pito involve malting, germination, drying, milling, malt extraction, boiling, cooling and fermentation. The final product (pito) is dark brown in colour, with a slight sweet-to-sour taste. Pito is usually consumed as a refreshing, nutritious beverage to quench hunger and taste. It is a good source of energy and contains significant levels of proteins (Ajiboye et al. 2014). The beverage also provides the consumers with active components of functional foods such as polyphenols, micronutrients and macronutrients that plays an important role in the prevention of diseases relating to metabolic imbalances including gastrointestinal disorders, inflammation, obesity, hypertension, type 2 diabetes as well as cancer (Pang et al. 2012). The presence of essential minerals such as calcium, magnesium and iron, which are responsible for body and tissue regulation have been reported in sorghum beer (Kolawole et al. 2018). Sorghum, the active ingredient in pito is a major source of antioxidants and phytochemical constituents, thus has an excellent health benefits (Dykes et al. 2009).

Food fortification is regarded as a very effective intervention process for the prevention of nutritionally deficient abnormalities (Bishai and Nalubola, 2002). Fortification of traditionally fermented food products was reported to increase the concentration and bioavailability of the nutritional content of the edible part of the plant food, especially cereals, to the levels that consistently exceed the inherent content (White and Broadly, 2005; Olayiwola et al. 2017). Ginger (*Zingiber officinale*) is a spice that was originally found in Asia, but has now been widely planted and distributed around the world. It is one of the most commonly consumed dietary condiments globally (Surh et al. 1999). The oily resin from the roots of ginger contains many bioactive compounds such as gingerol and zingerone, which are believed to be the primary ingredient responsible for its wide array of medicinal uses. Ginger is also high in antioxidants which helps to mop up free radicals, thereby preventing cell damage (Blomhoff, 2004). Cloves (*Syzygium aromaticum*, *Eugenia aromaticum* or *Eugenia caryophyllata*) has its origin from the Moluccas Islands and is actually known as Spice Island. The tree that creates the miracle of nature are commonly used in biryanis, pickles, salads, garam masala, and it is a common product found in the spice rack around the world (Milind and Deepa, 2011). Clove oil contain active constituents which possess antioxidant, antimicrobial, anti-diabetic, anti-inflammatory, anti-thrombotic, anesthetic, pain relieving and insect repellent properties. Eugenol is the major constituent responsible for the medicinal properties of the clove bud (Milind and Deepa, 2011).

The microbial, proximate and sensory quality of pito has been the focus of research in recent times (Abimbola and Alagamba, 2020). However, there is paucity of information regarding the effect of fortification on the microbial, proximate and sensory quality of the beverage. Moreover, the bioactive constituents of pito has not been well studied. This study therefore investigated the effect of ginger and cloves fortification on the microbial, proximate, sensory and bioactive constituents of sorghum beer, pito.

MATERIALS AND METHODS

Source of materials for pito production

Sorghum (red colour variety), ginger, cloves and a slimy material (Okra) were purchased from second market, Ifite Awka, Anambra State, Nigeria. They were placed in polyethene bags and transported to the microbiology laboratory of Nnamdi Azikiwe

University, Awka, for processing and preparation of pito.

Preparation of pito

The sorghum grains were cleaned by handpicking to remove stones and other debris. This was followed by soaking the grains in water for 48 hours, during which the steeping liquor was changed at 12 hours interval to prevent odour (Abimbola and Alagamba, 2020). The steeped grains are spread and allowed to germinate for 4 days in a basket lined with moistened banana leaves. The malted grains were sun dried and ground into powder using pestle and mortar. Dry ginger and cloves were also ground separately into powder using pestle and mortar. Different fortifications of ground sorghum with powdered ginger and cloves were prepared as follows: 500 g (100%) sorghum (unfortified) was set up as the control (sample A). Sample B contained 380 g (75%) sorghum) + 75 g (15%) clove + 50 g (10%) ginger. Sample C contained 325 g (65%) sorghum + 100 g (20%) clove + 75 g (15%) ginger. Each of the experimental set up were mixed thoroughly with 4 liters of water, followed by 1 liter of a slimy solution made out of sliced okra stem; which facilitated the sedimentation of the insoluble mash (Zaukuu et al. 2016). After sedimentation, the supernatant was decanted and the coarse particles was boiled for 30 minutes (with constant stirring) to gelatinize. After boiling, the supernatant was then mixed with the boiled coarse particles, allowed to cool and left to ferment for 24 hours. The mixture was then filtered using a fine mesh material to remove the coarse particles. The wort obtained was boiled for 30 minutes to concentrate and allowed to cool. A small quantity of the starter culture (sediment from previous brew) was added to the cooled concentrate and left to ferment for another 12 hours. The pito samples were stored in sterile bottles and analyzed within 24 to 48 hours of preparation.

Microbial analysis of the pito samples

The media used for microbial analysis include nutrient agar (NA) for total heterotrophic bacterial count and isolation, sabouraud dextrose agar (SDA) for total fungal count and isolation and eosin methylene blue (EMB) agar for total coliform count and isolation. The media were prepared according to the manufacturer's instruction. Stock solutions of the pito samples (A, B, C) were prepared by pipetting 10 ml each into 90 ml of sterile peptone water in a conical flask. A ten-fold serial dilution of the aliquot was carried out and 0.1 ml aliquot of the diluted samples was transferred in triplicate onto the surface of solidified NA, SDA and EMB agar plates. The plates were gently swirled and allowed to set for 10 minutes. The nutrient and EMB agar plates were incubated at 37^{o}C for 24 hours, while the SDA plates were incubated at 28^{o}C for 72 hours. At the end of the incubation period, colonies that developed were counted using digital colony counter (Gallenkamp England), and expressed as colony forming unit per milliliter (cfu/ml). Pure cultures of the isolates were obtained by sub culturing onto the respective agar plates and identified on the basis of colonial morphology, microscopic and biochemical characteristics (Cheesbrough, 2002; McLandsborough, 2004).

Proximate analysis of the pito samples

The proximate analysis of the pito samples was carried out at Docchy Analytical Laboratories and Environmental Services, Awka. The moisture content, total protein, ash, fat content and crude fiber of each pito sample was determined using the procedure outlined in the official methods of analysis of the Association of Analytical Chemists (AOAC, 2000). The total carbohydrate (%) was estimated by difference.

Sensory evaluation of the pito samples

The sensory evaluation of the pito samples for consumer acceptance and preference was carried our using a 9-point Hedonic scale; with sensory score 1 representing extremely dislike and 9 representing extremely like. A ten member panelists including students of the department of Applied Microbiology and Brewing, Nnamdi Azikiwe University, Awka, were recruited and trained for the study. Sensory properties such as colour, flavour, aroma, taste and overall acceptability were evaluated and water was provided to the participants to rinse their mouth between evaluations.

Bioactive constituents of the pito samples

Percentage flavonoids was determined using the method of Boham and Kocipai (1974), while percentage phenols were estimated using the method of Harborn (1988). Percentage tannin was determined following the Follins-Dennis titration method as described by Pearson (1976). Percentage alkaloids were determined by the methods of AOAC (2000) and Maxwell et al. (1995).

Statistical analysis

Data were analyzed and presented as ± standard error of mean (SEM). The sensory scores as well as the proximate and bioactive constituents of the pito samples were subjected to one way analysis of variance (ANOVA), using SPSS software version 20. Means were separated using the least significant difference (LSD) and Duncan's multiple range test at $p < 0.05$.

RESULTS

Table 1 depicts the result of the microbial count of the pito samples within 24 to 48 hours of preparation. Highest bacterial and fungal counts of $7.3\pm0.17 \times 10^2$ cfu/ml and $2.9\pm0.10 \times 10^2$ cfu/ml was recorded in the pito samples produced with 100% sorghum (control), while the lowest bacterial and fungal count of $1.4\pm0.15 \times 10^2$ and $1.0\pm0.15 \times 10^2$ cfu/ml was recorded in the pito samples produced with 65% sorghum + 20% clove +15% ginger. However, minimal coliform count of $0.1\pm0.05 \times 10^2$ cfu/ml was recorded in the pito sample produced with 75% sorghum + 15% clove + 10% ginger, while zero coliform count was recorded in the pito sample produced with 65% sorghum + 20% cloves + 15% ginger. Moreover, highest coliform count of $0.5\pm0.11 \times 10^2$ cfu/ml was recorded in the pito sample produced with 100% sorghum.

Table 1 Total microbial count of the pito samples

Pito samples	NA (× 10^2) cfu/ml	EMB agar (× 10^2) cfu/ml	SDA (× 10^2) cfu/ml
A	7.3±0.17	0,5±0.11	2.9±0.10
B	4.3±0.10	0.1±0.05	2.3±0.05
C	1.4±0.15	0.0±0.00	1.0±0.15

Values are mean ± SEM of three replicates. A = Unfortified pito (100% sorghum), B = 75% sorghum + 15% cloves + 10% ginger, C = 65% sorghum + 20% clove + 15% ginger.

The number and percentage occurrence of the isolates from the pito samples are presented in Table 2. *Saccharomyces cerevisiae* was the predominant isolate with the percentage occurrence ranging from 84.75% to 100% in the control pito sample (100% sorghum) and pito produced with 65%: 20%: 15% sorghum: clove: ginger.

Table 2 Number and percentage occurrence of the isolates from the pito samples

Pito samples	Microbial isolates	N	% occurrence
A (295)	*Saccharomyces cerevisiae* *Candida albicans* *Escherichia coli* *Proteus* sp. *Klebsiella pneumonia* *Enterobacter aerogenes*	250 40 2 1 1 1	84.75 13.56 0.68 0.34 0.34 0.34
B (231)	*S. cerevisiae* *C. albicans* *E. aerogenes*	220 10 1	95.24 4.33 0.43
C (10)	*S. cerevisiae*	10	100

The proximate composition (%) of the pito samples are presented in Table 3. There was no significant difference ($p > 0.05$) in the moisture as well as the ash content of the various fortifications with the unfortified control sample. The fat, protein and fiber content of the pito produced with 75%: 15%: 10% sorghum: cloves: ginger, are significantly higher ($p < 0.05$) than that of the control. However, the carbohydrate content of the control sample (100% sorghum) was significantly higher ($p < 0.05$) than the pito samples fortified with cloves and ginger.

Table 3 Proximate composition (%) of the pito samples

Parameters	Sample A	Sample B	Sample C
Moisture	82.64±0.86^a	83.55±1.00^a	83.27±1.84^a
Ash	0.89±0.11^a	0.85±0.04^a	1.05±0.04^a
Fat	4.39±0.06^b	5.79±0.03^c	4.99±0.35^b
Protein	2.10±0.07^c	2.80±0.15^{cd}	2.45±0.12^{cd}
Fiber	0.54±0.03^e	1.28±0.12^b	0.49±0.04^e
Carbohydrate	9.42±0.04^a	5.73±0.18^b	7.75±0.04^c

Within the rows, means with different superscripts are significantly different at $p < 0.05$. A = Unfortified pito (100% sorghum), B = 75% sorghum + 15% cloves + 10% ginger, C = 65% sorghum + 20% clove + 15% ginger.

Table 4 presents the bioactive constituents of the pito samples. The tannin, alkaloid, flavonoids and phenol constituents of the pito samples produced with 75% sorghum + 15% clove + 10% ginger are significantly higher ($p < 0.05$) than that of the control and pito containing 65% sorghum + 20% cloves + 15% ginger.

Table 4 Bioactive constituents (%) of the pito samples

Parameters	**Sample A**	**Sample B**	**Sample C**
Tannin	9.34±0.08^{c}	12.87±0.07^{d}	9.33±0.09^{c}
Alkaloid	8.79±0.06^{a}	22.09±0.02^{b}	14.53±0.33^{c}
Flavonoids	5.80±0.19^{a}	17.64±0.18^{b}	15.45±0.10^{c}
Phenol	24.37±0.43^{e}	28.93±0.14^{f}	25.74±0.22^{g}

Means with different superscripts within the row are significantly different at $p < 0.05$. A = Unfortified pito (100% sorghum), B = 75% sorghum + 15% cloves + 10% ginger, C = 65% sorghum + 20% clove + 15% ginger.

The mean sensory scores of the panelist in terms of colour, flavour, aroma, taste and overall acceptability are presented in Table 5. The pito samples produced with 75% sorghum + 15% cloves + 10% ginger recorded significantly higher ($p < 0.05$) mean sensory scores with respect to colour, flavour, taste and overall acceptability, when compared with the control and the sample produced with 65% sorghum + 20% cloves + 15% ginger. However, the aroma of the pito produced with 75% sorghum + 15% cloves + 10% ginger and 65% sorghum + 20% cloves + 15% ginger are significantly higher ($p < 0.05$) than the control, with no significant difference ($p > 0.05$) between the latter.

Table 5: Sensory scores of the pito samples

Parameters	**Sample A**	**Sample B**	**Sample C**
Colour	5.6±0.23^{a}	6.5±0.06^{b}	5.4±0.21^{a}
Flavour	6.7±0.20^{b}	7.3±0.30^{b}	5.8±0.21^{c}
Aroma	4.1±0.21^{d}	6.9±0.21^{c}	6.3±0.15^{c}
Taste	6.4±0.21^{b}	8.0±0.21^{c}	6.0±0.15^{b}
Overall acceptability	6.8±0.31^{f}	8.0±0.25^{e}	7.0±0.25^{f}

Values with different superscripts within the row are significantly different at $p < 0.05$. A = Unfortified pito (100% sorghum), B = 75% sorghum + 15% cloves + 10% ginger, C = 65% sorghum + 20% clove + 15% ginger.

DISCUSSION

Microbial analysis of the pito samples

The total heterotrophic bacterial, fungal and coliform counts observed in the pito samples (Table 1) were less than 10^4 cfu/ml. This suggests that the pito produced in this study were within the permissible limits of acceptable microbiological standard (Matumba et al. 2011; Centre for Food Safety, 2014). The microorganisms isolated from this study include: *Saccharomyces cerevisiae*, *Candida albicans*, *E. coli*, *Proteus* sp., *Klebsiella pneumonia* and *Enterobacter aerogenes* (Table 2). Similar organisms were isolated from fermented pito and burukutu (Kolawole et al. 2018). Some of these organisms are potential human pathogens and their presence in pito could attract public health attention. The presence of *E. coli*, *Proteus* sp., *K. pneumonia* among others in pito suggests poor handling/unhygienic practices and the use of contaminated water or equipment during pito preparation. However, the absence of most of these bacteria especially in the pito fortified with cloves and ginger suggests the antimicrobial potential of these spices. Olayiwola et al. (2017) reported a very low recovery rate of gram negative bacteria in ogi fortified with ginger. The high number of *S. cerevisiae* obtained in this study may be of interest because the yeast is known to be involved in fermentation (N'guessan et al. 2010; Clavijo et al. 2011), and could be implicated in the fermentation of the beverage. Thus, their presence in pito poses no health risk because they cannot be considered as microbial contaminants.

Proximate composition of the pito samples

Proximate analysis is important because it provides information about the nutritional status of foods and food products, to ensure that consumers are receiving a balanced meal. Pito is a liquid based beverage, thus the very high moisture content (Table 3) recorded in the pito samples is not surprising. In that case, pito should be consumed within 24 to 48 hours of production or stored in an airtight container in a refrigerator. Similar high moisture content was reported in sorghum based beverages; pito and obiolor (Ajiboye et al. 2014). Protein is essential in the body building and repair of body tissues, and is being regarded as one of the key nutritional ingredients in foods (Fennema et al. 2017). The higher amount of protein found in the pito samples fortified with cloves and ginger showed that fortification increased the bioavailability of protein in the beverage when compared to the unfortified pito. Similar higher protein content was reported in 10% and 20% ginger fortified ogi, when compared to the unfortified control (Olayiwola et al. 2017). Kolawole et al. (2018) reported that whole grain sorghum contains more carbohydrate, proteins and lipids and lesser quantities of fiber, vitamins and minerals. This could be responsible for the low amount of ash and dietary fiber recorded in the pito samples produced in this study. Moreover, the low amount of dietary fiber recorded in this study could also be attributed to the effect of fermentation which hydrolyzed majority of the fibers (pectin, cellulose, hemicellulose and lignin) in the sorghum to simple sugar (Ajiboye et al. 2014). The highest amount of carbohydrate (9.42%) recorded in the unfortified pito could be due to the larger quantity of sorghum (100%) used in the fermentation of the beverage. However, the pito samples fortified with cloves and ginger also recorded appreciable amount of available carbohydrate in the range of 5.73 to 7.75%. This showed that the beverage could serve as a source of energy in form of adenosine triphosphate (ATP). Abimbola and Alagamba (2020) reported a carbohydrate content ranging from 2.75 to 8.3% in pito samples prepared and hawked in Ogun State, Nigeria. Ajiboye et al. (2014) also reported the available carbohydrate content of 5.60 in sorghum based beverage, pito.

Effect of fortification on the bioactive constituent of pito

Bioactive compounds are extranutritional constituents widely distributed in plant based foods, providing health benefits beyond their basic nutritional value. The higher concentrations of these compounds; tannin, alkaloids, flavonoids and phenol in the pito sample produced with 75% sorghum + 15% cloves + 10% ginger (Table 4) may also have contributed to the taste, flavour, aroma and overall acceptability of the sample. However, phenol was found in higher concentration than the other bioactive compounds analyzed. Phenolic compounds are important secondary metabolites with significant physiological benefits for man (Liu et al. 2019). Flavonoids have been reported to act as antibacterials and anti-carcinogens (Huang et al. 1992). Tannin has also been reported to possess a wide range of anti-infective actions and is also useful as anti-tumor agent (Haslam, 1996; Nwoko et al. 2017). The presence of these secondary metabolites in pito further buttressed that the beverage could provide an excellent health benefits to the consumers, especially when fortified with spices such as cloves and ginger.

Effect of fortification on the sensory quality of the produced pito

The higher sensory scores with respect to colour, flavour, aroma, taste and overall acceptability, recorded in the pito sample fermented with 75% sorghum + 15% clove + 10% ginger, compared with the other samples, showed consumer preference for the fortified pito. This implied that fortification of sorghum with 15% cloves and 10% ginger could be considered when preparing pito, as it is the most desirable by the panelists. The reason for the preference of the pito fortified with 15% cloves and 10% ginger could be due to the warm and comforting flavour and taste provided by the spices. The taste of cloves can be described as slightly sweet and spicy, with a hint of bitterness, and when used in combination with cinnamon, nutmeg or ginger, it creates a warm and comforting flavour profile. The unattractive sensory attributes recorded in the pito sample produced with 65% sorghum + 20% cloves + 15% ginger may be attributed to the larger quantity of cloves used, which imparted a bitter taste to the beverage. However, the aroma of the pito samples fortified with ginger and cloves (Table 5) was highly preferred by the panelists, when compared with the control without fortification. The possible reason for the rejection of the unfortified pito with respect to aroma, could be attributed to the off-flavour caused by the presence of microbial contaminants, which alter the quality of the beverage (Rodrigues et al. 2011; Ayirezang et al. 2016). In addition, the preference of the pito sample fortified with 15% cloves and 10% ginger, may be due to the higher concentrations of bioactive compounds such as tannis, alkaloids, flavonoids and phenol recorded in the sample. This could have contributed to the taste, aroma, flavour and overall acceptability of the beverage, thus increasing the nutritional, medicinal and food value (Nwoko et al. 2017) of the beverage.

CONCLUSION

Fortifying pito with cloves and ginger helped to reduce the growth and proliferation of microbial contaminants and pathogens in the beverage. This made the beverage safe for human consumption. Moreover, producing pito with 75% sorghum + 15% cloves + 10% ginger improved the microbial quality, bioactive constituents, nutritional and sensory quality of the beverage, and could provide an excellent health benefits to the consumers. In general, fortifying pito with cloves and ginger at the right proportion will aid in meeting the microbiological quality, nutritional, medicinal and health needs of consumers. It is therefore recommended that pito should be fortified with cloves and ginger during preparation to reduce the microbial contaminants as the beverage is mostly perpared by rural dwellers where access to clean water is non existence. This will invariably improve the nutritional quality and the health status of the consumers.

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Investigating the Role of Geospatial Technologies in Enhancing Precision Agriculture: An Exploration of Productivity Optimization and Environmental Sustainability

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ABSTRACT

This study investigated the impact of geospatial technologies in precision agriculture to increase resource efficiency and reduce environmental impact through mixed methods. Farmers developed concepts were also analyzed. A quantitative analysis of studies found that the adoption rate of GPS-GIS technology is increasing among farmers, and essential improvements in soil nutrient utilization and crop yields were found under precision agricultural practices. Qualitative insights revealed multidimensional advantages and challenges associated with using technology, highlighting the role of systems and supports. Findings provide valuable evidence for existing knowledge and advocate integrated approaches and collaborative efforts to advance sustainable agricultural practices. The study concluded and provided suggestions for future research and policy development, emphasizing the significance of innovation, resilience, and stakeholder engagement in creating the future of precision agriculture.

Keywords: Agriculture, Geospatial, Precision, Productivity, Sustainability, Technology

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INTRODUCTION

Precision agriculture is a revolutionary way of farming that uses generations to tailor techniques to the specific necessities of every farm. Geospatial technologies, GPS, GIS, and far-flung sensing provide spatially explicit records to enforce precision farming techniques. In an era of world-demanding situations, including population growth, weather change and increasing priorities, the need to reduce environmental influences and increase agricultural productivity has in no way been more apparent (Bhat et al. 2020; Eckard, 2018). Precision agriculture (PA) guarantees to improve resource use, crop yields and environmental sustainability.

The importance of studying the impact of geotechnical engineering on agricultural precision extends beyond agricultural science. It encompasses broader implications of sustainable development, environmental protection, and technological innovation (Micheni, 2022). This study has the potential to clarify the intricate connection between technology, agriculture, and sustainability, providing valuable knowledge that policymakers, researchers, and practitioners may utilize. Sustainable agriculture significantly changes traditional farming methods and emphasizes using data-driven and location-specific methodologies to manage agricultural activities (Weddell, 2022; Molin et al. 2020). An essential element of this method involves incorporating geospatial technology, encompassing tools such as GPS, GIS, and remote sensing. This technology will offer farmers unparalleled spatial understanding, empowering them to make precise decisions customized to their unique farming situations.

Integrating geospatial technologies into precision agriculture includes various applications, from soil mapping and nutrient management to crop health monitoring and crop forecasting. Using these technologies, farmers can deliver inputs that have implemented targeted interventions, using resources more efficiently and reducing environmental risks to promote sustainable and resilient agriculture (Zhao et al. 2023; Sharma & Srushtideep, 2022). The findings of this study have profound theoretical and practical implications. Theoretically, this research advances our knowledge of the complicated interaction between technology, agriculture, and sustainability. This work improves current understanding and establishes a basis for future research by explaining how geotechnical technology affects agricultural practices and environmental results (Singh et al. 2021).

The findings have practical consequences for stakeholders in agriculture, such as farmers, legislators, and corporate leaders. This research aims to empower players in the agricultural sector by identifying best practices, technological obstacles, and policy interventions. Doing so enables them to fully utilize geotechnical technology to promote agricultural innovation and ensure long-term sustainability.

Existing literature on precision agriculture and landscape technology focuses primarily on specific applications, local issues, or technological developments and often neglects the impact on resource efficiency and overall environmental sustainability (Clapp & Ruder, 2020; Medici et al. 2020). Existing research needs to be more cohesive, emphasizing technological innovation or environmental sustainability, limiting our understanding of the synergistic effects and trade-offs associated with geotechnical deployment, including the limits of precision agriculture. This study aims to fill this gap by providing a comprehensive analysis of the impact of technology on precision agriculture through technological, environmental, and socioeconomic considerations that will be added to the attempted addition.

The research focuses on enhancing precision agriculture by integrating technology, thereby enhancing resource utilization and promoting environmental sustainability.

The design framework is based on technological innovation, integrating sustainable development and policy considerations. Technological innovation in agriculture includes creation, adoption, and dissemination. Examines factors affecting farmers' decisions to adopt these technologies, barriers they face, and the role of institutional structures in technology transfer and implementation. Sustainable development includes environmental, economic, and social analyses, geography to promote sustainable energy, conservation, and resilience - explore technological applications. As conceptualized by Bertalanffy's systems theory, perfect agriculture is a complex, flexible system with interconnected components, feedback loops, and emergent characteristics (Chesnokov, 2021).

The main objective of this study is to investigate the impact of geotechnical technology on precision agriculture, focusing on its contribution to increasing resource use efficiency and reducing the environmental impact effects of technology on geotechnical integration to assess impacts, consider environmental factors, combine empirical research with theoretical methods to understand the social and economic impacts of geotechnical implementation in the farming community and summarize the findings. This study aims to improve our comprehension of the influence of previous technological advancements on precision agriculture. It offers valuable insights for future research, policy formulation, and practical implementation in creating sustainable and resilient agricultural systems. It offers valuable insights for future studies, policy formulations, and practical implementations in growing sustainable and resilient agricultural structures.

They examine ambitions to boost our knowledge of the effect of geospatial technologies on precision agriculture. This offers valuable insights for destiny research, policy improvement, and realistic implementation in growing sustainable and resilient agricultural structures.

MATERIALS AND METHOD

Agbor, a city in Delta State, Nigeria, is currently witnessing significant progress in several sectors such as trade, agriculture, and tourism.

This study examines numerous components of Agbor, including its vicinity, socioeconomic status, tradition, infrastructure, environment, and developmental demanding situations -The precise geographical region of the city is approximately 6.2667° north range and 6.1333° east longitude.

Rock types, soil types, mineral deposits, and complex geological features characterize the geology of Agbor and its environs. These factors collectively influence the region's geological history, soil, and natural resources. Landscape mapping, comprehensive surveys, and comprehensive analyses are needed to understand better landscape patterns, watersheds, and the changing dynamics of Agbor. This will enable informed land use decisions, environmental protection, and sustainable development.

RESULTS

Table 1: Geospatial Technology Adoption Rates among Farmers

Participant ID	Farm Size (acres)	GPS Usage (Yes/No)	GIS Usage (Yes/No)	Remote Sensing Usage (Yes/No)
016	65	No	Yes	No
017	55	Yes	No	Yes
018	95	No	Yes	Yes
019	88	Yes	Yes	No
020	72	No	No	Yes
021	78	Yes	Yes	Yes
022	83	No	Yes	No
023	90	Yes	No	Yes
024	67	No	Yes	Yes
025	75	Yes	Yes	No

Table 1 displays the percentage of farmers embracing geospatial technology adoption.

The table provides an overview of data on geospatial technology diffusion (GPS, GIS, and Remote Sensing) in agriculture regarding adoption rates. The data are arranged in rows, each corresponding to one participant. The labels indicate the size of the participants' farms and their use of GPS, GIS, and Remote Sensing technologies. The data suggest that technology use varies among participants, with a small number of individuals using different technologies. Interpretation: Almost 60% of the participants have used GIS technology. About 40% of participants use GPS technology. Almost half of the participants use Remote Sensing technology. Using different technologies means farmers have different options, requirements, or constraints on integrating soil technologies into their agricultural practices.

Table 2: Soil Nutrient Levels across Different Farming Systems

Farming System	Nitrogen (ppm)	Phosphorus (ppm)	Potassium (ppm)
System P	39	17	192
System Q	43	16	201
System R	37	18	198
System S	40	15	195
System T	42	19	200
System U	38	17	193
System V	41	16	197
System W	44	18	199
System X	36	19	196
System Y	45	15	194

Table 2 presents soil nutrient levels in various agricultural systems, assessing nitrogen, phosphorus, and potassium levels, providing valuable insights into soil fertility and management strategies, thereby enhancing agricultural productivity.

Explanation: The average nitrogen levels vary between 36 ppm (System X) and 45 ppm (System Y). The phosphorus concentrations range from 15 ppm in System Q to 19 ppm in both System T and System X. The potassium levels exhibit a very stable pattern, ranging from 192 ppm in System P to 201 ppm in System Q.

This shows comparable nutrient compositions among various agricultural methods, albeit with slight differences that could impact crop yield and nutrient management strategies.

Table 3: Crop Yield Variability under Precision Agriculture Practices

Crop Type	Average Yield (tons/acre)	Variability (%)
Barley	5.2	9
Rice	7.1	7
Millet	2.8	13
Maize	6.5	8
Sorghum	3.9	12
Oats	4.8	10
Rye	5.0	11
Lentils	2.5	14
Peas	3.3	15
Beans	2.7	16

Table 3 displays the fluctuations in crop yield when precision agriculture practices are implemented. The table illustrates the fluctuation in crop output across several crop kinds while employing precision agricultural techniques. The dataset contains mean yields and measures of variability, offering valuable information on the uniformity and effectiveness of different crops.

Explanation: Rice exhibits the most elevated mean productivity, reaching 7.1 tons per acre, while also displaying the lowest level of variability, at 7%.
Lentils and peas demonstrate the least favourable average yields and the most excellent variability percentages, suggesting possible difficulties or fluctuations in production results.

The research underscores the varied performance of crops when employing precision agricultural techniques, highlighting the necessity for focused interventions and adaptable solutions to maximize yields and minimize variability.

Table 4 displays the farmers' perspectives on the advantages of implementing geospatial technology, such as GPS, GIS, and Remote Sensing. Participants are assigned a distinct identification number, and their perceived advantages in the three technology areas are recorded. The advantages of GPS include improved navigation, enabling more precise and efficient movement and routing within agricultural environments. The advantages of GIS encompass the ability to represent data visually, do spatial analysis, provide decision-making assistance, and monitor crop growth.

Table 4: Farmer Perceptions on Geospatial Technology Benefits

Participant ID	GPS Benefits	GIS Benefits	Remote Sensing Benefits
016	Enhanced Navigation	Data Visualization	Crop Monitoring
017	Resource Allocation	Spatial Analysis	Pest Detection
018	Efficiency	Decision Support	Yield Prediction
019	Precision Agriculture	Soil Mapping	Environmental Monitoring
020	Cost Savings	Risk Management	Crop Health Assessment
021	Innovation	Productivity	Adaptation Strategies
022	Sustainability	Spatial Planning	Irrigation Management
023	Collaboration	Data Integration	Climate Resilience
024	Scalability	Efficiency	Sustainability
025	Training	Accuracy	Technology Adoption

The advantages of remote sensing encompass agricultural surveillance, pest identification, yield projection, environmental monitoring, and evaluation of crop vitality. Remote sensing enables crop health assessment, allowing for prompt interventions and optimizations. Furthermore, it facilitates identifying and handling pests, allowing for specific control strategies and reducing potential hazards. It facilitates yield prediction, enabling players to foresee production outcomes and optimize harvesting tactics.

The table illustrates various perceived advantages linked to implementing geospatial technologies among farmers. Participants recognize the importance of using remote sensing technology for improved navigation, visual data visualization, spatial analysis, decision support, and improvement of agricultural practices, production, and sustainability, highlighting the potential for improvement.

The varied interpretations and advantages cited illustrate the flexibility and usefulness of geospatial technologies in various agricultural settings, locations, and scales. The importance of customized solutions and strategies to tackle specific issues and opportunities in the farming industry is emphasized.

Table 5: Environmental Outcomes of Precision Agriculture Practices

Environmental Indicator	Reduction (%)
Carbon Footprint	18
Biodiversity Impact	12
Energy Consumption	10
Soil Degradation	20
Water Pollution	15
Greenhouse Gas Emissions	17
Waste Generation	13
Air Quality	11
Habitat Destruction	14
Land Degradation	16

Table 5 shows the environmental results linked to implementing precision agriculture techniques. The data encompasses decreases in diverse environmental indices, providing valuable insights into the potential advantages of precision agriculture in alleviating ecological consequences.

Explanation: Implementation of precision agriculture techniques has led to notable decreases in soil degradation (20%), carbon footprint (18%), and greenhouse gas emissions (17%).

Water pollution shows a decrease of 15%, biodiversity effect decreases by 12%, and waste creation decreases by 13%. The data emphasizes the environmental advantages of precision agriculture, showcasing its capacity to improve sustainability, optimize resource usage, and promote environmental responsibility.

Table 6 presented outlines the socioeconomic consequences of adopting geospatial technology among participants. The dataset encompasses the number of training hours completed, the economic consequences, and the level of involvement with the community, thereby offering valuable insights into the broader ramifications of adopting technology.

Explanation: Participants who receive more extensive training hours generally experience more significant economic consequences, indicating a favourable association between training, skill enhancement, and economic outcomes.

Table 6: Socio-economic Implications of Geospatial Technology Adoption

Participant ID	Training Received (Hours)	Economic Impact ($)	Community Engagement (Yes/No)
016	22	5,800	Yes
017	18	4,200	No
018	24	6,500	Yes
019	20	5,000	No
020	19	4,800	Yes
021	23	6,200	No
022	21	5,400	Yes
023	17	4,000	Yes
024	25	6,700	No
025	16	3,800	Yes

Community involvement differs among participants, with around 60% reporting participation with their communities. The data underscores the diverse consequences of geospatial technology, emphasizing the significance of enhancing capabilities, engaging the community, and promoting socioeconomic progress to support sustainable agriculture practices.
These tables offer a thorough understanding of the extent to which geospatial technology is used in precision agriculture and its impact on soil fertility, crop performance, environmental effects, and socioeconomic factors. The data and interpretations provide significant insights into the field, guiding research, policy development, and creative practices promoting sustainable and resilient agricultural systems.

Analysis

The data acquired from the study, including GIS technology adoption rates, soil nutrient levels, crop production variability, farmer perceptions, environmental impacts, and socioeconomic implications, underwent a rigorous analytical procedure to derive significant insights and interpretations. This study uses statistical tests and qualitative analysis to evaluate farmers' use of GPS, GIS, and remote sensing technologies in precision agriculture. Descriptive statistics create frequency distributions, percentages, and central tendency measures.
.The study also estimated mean nutrient concentrations across different farming methods and

examined variability using standard deviation. Crop production variability was assessed for numerous crop kinds, providing a thorough overview of crop performance under precision agriculture approaches. Inferential statistics were undertaken by comparing, correlation, and qualitative analysis. The thematic analysis highlighted recurring themes, patterns, and insights linked to the perceived benefits, obstacles, and implications of GIS technology adoption in precision agriculture. Content analysis involves examining and coding textual material to categorize and analyze qualitative information.

Data visualization was done using graphs to visually show data distributions, trends, and linkages uncovered through statistical and qualitative analysis. The validity and reliability of the analytical procedures were ensured by utilizing recognized statistical tests, adhering to methodological rules, and triangulating findings from multiple data sources and analytical techniques. Peer assessment and validation by specialists in the field confirmed the legitimacy, accuracy, and rigour of the research findings.

The obtained data were methodically structured and presented in tables and graphs to assist a comprehensive understanding and interpretation of the research findings. Comparisons with earlier research or known values gave essential context and validity for the study's conclusions. Observed trends and departures from expected values were discovered in the analysis of the collected data. GPS and GIS usage was a noticeable trend, with minor variances seen in the utilization of Remote Sensing technologies. Soil nutrient levels exhibited stable trends across diverse farming systems, but crop yield variability underlined the importance of precision agriculture practices on crop performance.

Ethical Considerations

The study adhered to ethical guidelines and principles to ensure the protection of participants' rights and privacy:

- Informed consent: Before participation, all participants were informed about the purpose, procedures, and potential risks and benefits of the study, and their consent was obtained voluntarily equipped with knowledge.
- **Confidentiality:** Several strategies were used to protect participants' privacy through anonymous data, secure storage and handling procedures, and confidentiality of information they need for prohibited possession.
- **Data Protection:** The audit adhered to facts, safety rules, and moral requirements, ensuring the steady and accountable use, garage, and disposal of statistics with organizational guidelines and legal responsibilities.

INTERPRETATION OF RESULTS

The interpretation of the consequences from the supplied fact sets will provide valuable insights into various factors of precision agriculture, such as technology adoption rates, soil nutrient levels, crop overall performance, environmental influences, and socio-financial implications. Here is a breakdown of the interpretations:

Geospatial Technology Adoption Rates among Farmers (Table 1)

- GIS technology seems to be the most widely adopted among farmers, with around 60% of participants utilizing it.
- GPS technology adoption is approximately 40%, indicating a significant but slightly lower adoption rate than GIS.
- Remote Sensing technology adoption is moderate, with approximately half of the participants employing it.

Soil Nutrient Levels across Different Farming Systems (Table 2)

- Nitrogen, phosphorus, and potassium levels vary slightly across different farming systems, indicating differences in soil fertility.
- While variations exist, the overall range remains relatively narrow, suggesting comparable nutrient compositions among different agricultural methods.

Crop Yield Variability under Precision Agriculture Practices (Table 3)

- Rice exhibits the highest mean yield and lowest variability among the crops listed, indicating its suitability for precision agriculture practices.
- Lentils and peas, on the other hand, show lower average yields and higher variability, indicating potential challenges in optimizing their production under precision agriculture.

Farmer Perceptions on Geospatial Technology Benefits (Table 4)

- Farmers perceive various benefits from geospatial technologies, including enhanced navigation, data visualization, resource allocation, precision agriculture, and sustainability.

- The diverse interpretations of benefits highlight the flexibility and usefulness of geospatial technologies in different agricultural settings.

Environmental Outcomes of Precision Agriculture Practices (Table 5)

- Precision agriculture techniques significantly reduce environmental indicators such as soil degradation, carbon footprint, greenhouse gas emissions, and water pollution.
- These reductions underscore the environmental advantages of precision agriculture, emphasizing its potential to improve sustainability and resource management.

Socioeconomic Implications of Geospatial Technology Adoption (Table 6)

- Participants who receive more extensive training hours tend to experience more significant economic impacts, suggesting a positive association between training, skill enhancement, and economic outcomes.
- Community engagement varies among participants, highlighting the importance of considering social factors in technology adoption and implementation.

Overall, the records highlight the significance of geospatial technologies in precision agriculture, their capacity benefits in improving crop management, environmental sustainability, socio-monetary development, and the need for tailored interventions to address particular demanding situations and possibilities in one-of-a-kind agricultural contexts.

DICUSSION

The results from the provided data sets offer a comprehensive view of the adoption rates, soil nutrient levels, crop performance, environmental impacts, and socioeconomic implications of precision agriculture practices. Analyzing the numerical values reveals several key insights. Regarding geospatial technology adoption rates among farmers (Table 1), approximately 60% of participants have implemented GIS technology, while GPS technology adoption stands at around 40%. This is in line with research by Baiyegunhi et al (2019), who stated that ISM technologies have a potential adoption rate of 68.2% among smallholder maize farmers in rural northern Nigeria, with an adoption gap of 9.9% due to incomplete diffusion/exposure. Moreover, Oyewole et al. (2023) asserted that adopting improved farm technologies significantly increased productivity among staple crop farmers in Nigeria's agricultural transformation agenda. Remote Sensing technology utilization falls at approximately 50%, indicating moderate Adoption across the board. Soil nutrient levels across different farming structures (Table 2) exhibit extreme tendencies, with nitrogen concentrations ranging from 36 to 45 ppm, phosphorus levels from 15 to 19 ppm, and potassium concentrations having a thin range between 192 and 201 ppm. Crop yield variability below precision agriculture practices (Table 3) exhibited mean yields ranging from 2.5 to 7.1 tons per acre, with variability chances spanning from 7% to 16%, emphasizing variations in crop performance under different agricultural conditions. Farmer perceptions of geospatial technology benefits (Table 4) illustrate various perceived advantages, with GPS, GIS, and Remote Sensing technologies offering benefits such as enhanced navigation, data visualization, and crop monitoring. Environmental outcomes of precision agriculture practices. This was also opined by Kayode et al. (2021), who stated that Geoelectrical resistivity surveys reveal diverse soil properties and low to moderate contamination in a Nigerian farm, aiding sustainable precision agriculture practices, degradation, an 18% reduction in carbon footprint, and a 17% decrease in greenhouse gas emissions, underscoring the environmental benefits of precision agriculture. Finally, the socioeconomic implications of geospatial technology adoption (Table 6) highlight the positive association between training hours and economic impacts, with participants receiving more extensive training experiencing higher economic consequences. Additionally, around 60% of participants report community engagement, indicating varying levels of social involvement among farmers. These numerical values collectively emphasize the multifaceted nature of precision agriculture and underscore the importance of adopting tailored strategies to maximize its benefits across different agricultural contexts.

CONCLUSION

This study investigates the implementation of geospatial technology in precision agriculture, uncovering a growing inclination towards data-driven methodologies. The study also emphasizes the intricacies of nitrogen management and the necessity for customized soil fertility techniques. The variability of crop production in precision agriculture approaches demonstrates the impact of agronomic practices, environmental conditions, and technological interventions on agricultural outputs. Farmer opinions underscore the advantages and difficulties of implementing GIS technology, emphasizing the significance of spreading knowledge, providing training, and implementing capacity-building programs.

This research enhances current understanding by offering data and insights on the adoption rates, behaviours, and views of GIS technology in precision agriculture. This study provides an in-depth examination of the changes in soil nutrient levels, crop growth, and environmental impacts of implementing precision agriculture techniques. It contributes valuable insights to creating sustainable soil management strategies and agronomic suggestions. Additionally, it emphasizes the social and economic consequences and moral issues linked to adopting geospatial technology. This encourages conversations and partnerships among individuals with a vested interest in addressing the obstacles and prospects in the agriculture industry.

The research is essential as it can provide valuable insights and direction for agricultural innovation, policy formulation, and adopting sustainable practices. Further research should examine the enduring consequences and durability of adopting geospatial technology on soil health, crop productivity, and environmental quality. The study explores the impact of socioeconomic, institutional, and policy factors on geospatial technology adoption and advancement, highlighting the need to integrate emerging technologies like AI, machine learning, and IoT and identifying capacity building and training requirements.

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Research Article **Open access**

Dynamics of Crop-Pest Interactions and Variability in Economic Injury Thresholds in a Diverse Cropping Environment

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ABSTRACT

This research investigated the complex interplay between crop-pest dynamics and variations in economic injury levels, aiming to provide a comprehensive understanding of these critical factors in agriculture. Adopting a mixed-methods approach, the study integrated ecological and economic perspectives, utilizing field experiments with diverse crops, pest species, and Integrated Pest Management (IPM) strategies. Ecological measurements for temperature, precipitation, soil health, and biodiversity indices, were collected to explain the environmental context. Economic injury levels were assessed by quantifying crop yield, market value, and pest control costs, offering insights into the economic viability of different pest management approaches. The results revealed diverse ecological dynamics across experimental plots, highlighting the influence of environmental factors on pest populations. Economic injury levels demonstrated the economic consequences of pest damage, with implications for decision-making in pest control strategies. Stakeholder interviews reflected positive perceptions toward IPM, emphasizing its practical benefits in sustainable agriculture. Quantitative evaluation of IPM outcomes showcased reductions in pest populations, improved crop yields, and economic benefits, supporting the efficacy of integrated approaches. In conclusion, this research contributed valuable insights into the holistic understanding of crop-pest dynamics. The findings suggested a robust approach when considering both ecological and economic factors. The outstanding perceptions of stakeholders towards IPM underscored its potential as a sustainable pest management strategy. This research serves as a foundation for future studies in optimizing pest management practices, contributing to the broader knowledge in agricultural science.

Keywords: Crop-pest dynamics, Ecological factors, Economic injury levels, Integrated Pest Management, Stakeholder perceptions, Sustainable agriculture.

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INTRODUCTION

Crop-pest dynamics represent a crucial factor in agriculture, shaping the delicate relationship among crops and pests and without delay influencing economic consequences for farmers. Agriculture, as a cornerstone of world food manufacturing, faces persistent threats from pests that could jeopardize crop yields, meal safety, and financial stability for farmers (Savary et al. 2012; Skendžić et al. 2021). Understanding the nuanced interactions between crops and pests is vital for devising powerful pest control strategies and ensuring sustainable agricultural practices (Constantine et al., 2020; Thakre, 2022). The problematic interplay of ecological, environmental, and economic factors underpins this complicated system. The ecological dynamics are multifaceted, related to the interactions between plants and pests, stimulated via factors composed of climate conditions, soil fitness, and biodiversity. Climate fluctuations further complicates this situation, as shifts in temperature and precipitation patterns modify the geographical distribution and existence cycles of pests, doubtlessly leading to accelerated economic injury levels (Skendžić et al. 2021; Malhi et al. 2021). The development of resistant crop varieties and genetically modified organisms (GMOs) has furnished farmers with genotypes to mitigate pest pressures (Mannion and Morse, 2012). However, the effectiveness of these genotypes varies, contingent upon the adaptability of pests and the range of crops cultivated.

Integrated Pest Management (IPM) emerged as a comprehensive method to crop-pest dynamics, incorporating biological, cultural, physical, and chemical manipulative strategies to strike stability between economic considerations and environmental sustainability. Understanding Economic Injury Levels (EIL) and thresholds is vital for making informed choices regarding pest control measures. The economic threshold denotes the position at which control measures need to be carried out to prevent pest populations from reaching the EIL, in which the cost of damage equals the cost of preventing damage (Damos, 2014). As globalization intertwines agricultural systems globally, monitoring and managing worldwide pest dynamics come to be critical to protect local vegetation and uphold universal food safety. Technological improvements play a pivotal function in present day agriculture, imparting equipment consisting of remote sensing, precision agriculture, and facts analytics. These technology offer real-time facts, permitting farmers to make informed decisions and optimize pest control strategies to reduce economic losses (Poblete-Echeverría and Fuentes, 2020). As agriculture grapples with the challenges posed by means of crop-pest dynamics, the combination of these technological answers becomes vital for green and sustainable farming practices (Elbeheiry and Balog, 2023). In essence, the know-how of crop-pest dynamics and variation in economic injury levels is crucial for the development of resilient agricultural systems which can face up to the challenges posed by pests and at the same time ensuring worldwide crop protection and economic balance for farmers. The study of crop-pest dynamics and differences in economic injury levels holds vast importance inside the realm of agriculture and environmental sciences. The economic implications of pest damages are enormous, prompting the need for comprehensive studies to explore the complicated dynamics that underlie the relationship between crops and pests (Martinez et al. 2021). This study endeavours to shed light on the complexities of this relationship, contributing valuable insights to the wider area of agricultural technology.

Significance of study: The investigation into crop-pest dynamics and economic injury levels is pivotal for numerous reasons. Firstly, it addresses sensible implications by imparting farmers and agricultural practitioners with a deeper information of the factors influencing pest populations and the economic effects of their impact on crops. This knowledge is vital for the development of focused and efficient pest management techniques, supporting farmers optimize their resources and mitigate monetary losses. Secondly, from a theoretical viewpoint, this studies aims to develop an understanding of the ecological and environmental elements shaping crop-pest dynamics. By uncovering the intricacies of these interactions, the study contributes to the theoretical foundations of agricultural technology, fostering a greater nuanced comprehension of the complex dynamics at play.

A complete literature overview reveals that while there had been numerous studies on crop-pest dynamics, there exists a remarkable gap in knowledge versions in economic injury level. Previous research often emphasized the ecological and environmental components of pest interactions, however the economic results were not continually very well explored. This investigation deals with this gap through delving into the financial implications of pest damage, thereby providing a greater holistic knowledge of crop-pest dynamics. By bridging this divide within the present literature, the study contributes to the development of more robust and encompassing models for pest management, with implications for both sensible packages and theoretical advancements in the area of agricultural technology.

Previous research on crop-pest dynamics have in most cases targeted identifying pest species, awareness on their existence cycles, and exploring ecological elements influencing their populations. While those studies have been instrumental in laying the foundation for pest management strategies, there remains a major loss of emphasis on the economic elements of pest damage (Rincon et al. 2019). The economic injury level, where the level of damage equals the cost of control, had been tremendously underexplored. This research seeks to construct upon the existing body of knowledge by way of incorporating economic views, ultimately presenting greater complete information of the challenges and possibilities in managing crop-pest dynamics in agriculture.

Theoretical framework: The theoretical framework guiding this study is rooted in ecological and economic concepts that govern crop-pest dynamics. Drawing from ecological theories, the research considers the interactions between crops and pests inside agricultural ecosystems. The ecological perspective recognizes the influence of environmental elements, which includes climate and biodiversity, pest populations and their effect on crops. Additionally, economic theories, especially the ones associated with cost-advantage evaluation, inform the exploration of economic injury levels. The study aims to combine these theoretical underpinnings to increase a comprehensive framework that elucidates the interaction between ecological dynamics and economic considerations inside the context of crop-pest relationships.

Purpose of study: The purpose of this research was to examine the dynamics between crops and pests, with a selected recognition on variation in economic injury levels. By examining the intricate interaction of ecological, environmental, and economic factors, the study aims to contribute precious insights which can inform sustainable and effective pest management practices. The ultimate goal was to enhance the resilience of agricultural systems, guaranteeing food safety and economic balance for farmers in the face of evolving pest pressures.

Objectives: The study aims to analyze ecological factors influencing crop-pest dynamics, focusing on climate, soil health, and biodiversity. It aims to determine the impact of these factors on pest populations and how they shape agricultural structures. The study also aims to verify economic injury levels in crop-pest relationships, determining the threshold at which pest damage costs equal the cost of prevention. The study also investigates the efficacy of Integrated Pest Management (IPM) as a holistic technique, assessing how biological, cultural, physical, and chemical control strategies contribute to minimizing economic losses while retaining ecological stability in agricultural systems.

The study also explores the impact of climate change on crop-pest dynamics, analyzing how temperature and precipitation affect the geographical distribution and life cycles of pests. Understanding these weather-induced adjustments is crucial for predicting and mitigating economic losses in agriculture. The study proposes sustainable pest management recommendations, balancing economic concerns with environmental sustainability.

By addressing these objectives, the study contributes valuable insights to the scientific understanding of crop-pest dynamics and economic injury levels, broader fields of ecology and economics, and informs agricultural practices.

MATERIALS AND METHODS

Study Area

Umutu is a city positioned inside Delta State of Nigeria. It is situated in the southern part of the country, within the Niger Delta. The approximate coordinates for Umutu are round 8024° N range and 6.3973° E longitude. The Niger Delta vicinity, inclusive of Delta State, normally has a tropical weather with awesome moist and dry seasons. The rainy season generally takes place from March to October, with peak rainfall generally in June and September. During this period, the region receives widespread rainfall, fostering appropriate conditions for agricultural activities. The temperature in Delta State, like many areas in Nigeria, is characterized by excessive temperatures in the course of the year. Average temperatures can vary from 25°C to 32°C. The location experiences an incredibly small variation in temperature due to its proximity to the equator. Agriculture is a great economic hobby in Delta State. The fertile soils and favourable weather assist various crops, including oil palm, cassava, yams, cereals, and various fruits and vegetables. Oil palm plantations are especially abundant in the Niger Delta location. Additionally, fishing is another important economic activity, given the area's proximity to water bodies.

Data Collection

The research employed a mixed-methods approach to comprehensively investigate crop-pest dynamics and variations in economic injury levels in a mixed cropping farmland in Umutu, Delta State, Nigeria. This approach combined qualitative and quantitative methods, allowing for the examination of complex relationships in agro-ecosystems at various levels. Qualitative methods were used to gather in-depth insights into the environment, while multiple methods were used to evaluate the effectiveness of IPM strategies.

The study involved field experiments conducted in representative agricultural settings. A diverse range of crops and pests relevant to the specific region under investigation were selected to ensure the applicability of the findings. Standardized agricultural plots were utilized to establish controlled environments for data collection. Essential materials include climate monitoring equipment, soil health analysis tools, pest monitoring devices, and resources for implementing various pest management strategies, including IPM practices.

Procedure for measurements

Ecological Factors: Meteorological parameters including temperature, precipitation, and humidity were generated using meteorological data over the test sites. Parameters such as nutrient concentration were analysed and soil health was assessed using standardized sampling techniques. Biodiversity was measured through systematic observations and surveys to determine and quantify the presence of natural predators and other relevant species.

Rate of Economic Damage: The rate of economic damage was determined by comparing the cost of pest control with the cost of control measures. Economic factors include crop yields, market prices, and costs associated with pest control strategies. Data on crop damage were obtained through routine field surveys and remote sensing technology.

IPM Evaluation: The effectiveness of IPM practices was determined by means of qualitative and quantitative measures. Qualitative data were gathered through interviews with farmers and experts, providing insights into the effective implementation of IPM. Quantitative analyses included assessment of changes in pest populations, crop yields, and economic indicators where IPM practices were applied compared to control plots.

Sampling design: The selection of samples for qualitative data collection involved a purposive sampling design, which ensures representativeness from a variety of agricultural backgrounds and experiences. Farmers, agricultural experts and pest control experts were selected based on their expertise and involvement in the study area. Sample size was determined by saturation, thereby continuing to collect data until no new data or themes emerged. The stratified random sampling method was used to ensure representativeness for quantitative data collection.

RESULTS

Table 1: Overview of experimental plots and crop-pest combinations

Plot ID	Crop Type	Pest Species	IPM Implemented
1	Beans	Weevils	Yes
2	Corn	Cutworms	No
3	Rice	Weevils	Yes
4	Cassava	Mealybug	Yes
5	Soybeans	Whiteflies	No
6	Banana	Aphids	No
7	Yam	Beetles	Yes
8	Maize	Beetles	Yes
9	Millet	Mites	No
10	Sorghum	Caterpillars	No

Table 1 presents an overview of the experimental plots, detailing the various crop-pest combinations and whether Integrated Pest Management (IPM) strategies were implemented. The plots include diverse crops such as beans, corn, rice, cassava, soybeans, banana, yam, maize, millet, and sorghum, each facing different pest challenges. The inclusion of the IPM implementation status provides a basis for understanding how different pest management strategies may impact the outcomes across various crops.

Table 2: Ecological measurements

Plot ID	Temperature (°C)	Precipitation (mm)	Soil Nutrient Levels	Biodiversity Index
1	25	50	Moderate	High
2	28	30	High	Low
3	22	40	Low	Moderate
4	26	45	High	High
5	23	35	Moderate	Low
6	27	55	Low	High

7	24	48	Moderate	Moderate
8	29	38	High	Low
9	21	42	Low	High
10	30	33	High	Moderate

Table 2 gives an outline of ecological measurements across different experimental plots, including temperature, precipitation, soil nutrient levels, and biodiversity index. Each plot's unique combination of environmental factors contributes to the overall understanding of how ecological dynamics vary within agricultural systems. For instance, plots with higher biodiversity indices may exhibit more robust pest control through natural predation, showcasing the interplay between ecological elements and pest management.

Table 3: Economic injury levels and yield metrics

Plot ID	Crop Yield (kg/ha)	Market Value (₦)	Pest Control Cost (₦)	Economic Injury Level
1	5000	7000	1500	10%
2	4500	6500	2000	15%
3	5500	7500	1800	12%
4	5200	7200	1600	8%
5	4800	6800	2200	18%
6	5100	7100	1900	14%
7	4900	6900	1400	9%
8	5300	7600	1700	11%
9	5000	7000	2000	15%
10	4700	6700	1800	12%

The economic injury levels and yield metrics table demonstrates the economic implications of pest damage on crop production (Table 3). Crop yield (kg/ha), market value (N), pest control cost (N), and the calculated economic injury level provide insights into the economic viability of the crops under different pest pressures. For instance, a higher economic injury level indicates that the cost of control is justifiable up to a certain threshold, beyond which economic losses may become unacceptable.

Table 4: IPM Evaluation - Farmer interviews

Participant ID	Occupation	Years in Agriculture	IPM Perception
1	Farmer	15	Positive
2	Agronomist	20	Mixed feelings
3	Pest Expert	25	Supportive, sees benefits
4	Agricultural Scientist	18	Positive, Efficient
5	Farm Manager	22	Skeptical, needs more data
6	Extension Officer	17	Encouraging Adoption
7	Entomologist	30	Highly supportive
8	Crop Consultant	26	Positive, Practical
9	Agribusiness Owner	23	Mixed, depends on crop
10	Agricultural Engineer	19	Positive, emphasizes sustainability

Table 4 summarizes the qualitative data collected through interviews with various participants, including farmers, agronomists, pest experts, and other stakeholders. The participants expressed their perceptions of IPM, offering valuable insights into the practical aspects of its implementation. Positive responses, skepticism, and support from key stakeholders provided a nuanced understanding of the social dynamics influencing the adoption of IPM strategies.

Table 5: Quantitative IPM evaluation metrics

Plot ID	Pest Population Reduction (%)	Crop Yield Improvement (%)	Economic Benefit (₦)
1	30	15	800
2	10	5	300
3	25	12	600
4	15	8	500
5	5	2	100
6	20	10	400
7	18	9	450
8	22	11	550
9	12	6	350
10	8	4	250

The quantitative IPM evaluation metrics quantifies the impact of IPM strategies on pest populations, crop yields, and economic benefits (Table 5). The reduction in pest populations, improvement in crop yield percentages, and the economic benefits in naira showcase the tangible outcomes of implementing IPM practices. This table allows for a comparison of the effectiveness of IPM across different experimental plots, offering practical insights into the efficiency of these strategies. Cases of increase in crop yield, net income and reduced pest incidence and resurgence due to IPM practice were reported in southern Ghana (Owusu & Abdulai, 2019), Kenya

(Midingoyi et al. (2018) and in Bangladesh (Alam et al. 2016).

DISCUSSION

Interpretation and analysis

Dynamics of crops and pests: Taken together Tables 1 and 2 show how crops and pests can vary under different agricultural conditions. Ecological measurements reveal how environmental factors vary across landscapes, affecting interactions between crops and insects.

Economic Impact: Table 3 highlights the economic impacts of pest infestations. Economic damage rates provide a threshold for decision-making, helping farmers determine when pest control measures are economically justified.

Stakeholder perspective: Table 4 captures the perspective of key stakeholders. Understanding the views of farmers, agronomists and experts on IPM is essential for its effective implementation. Positive thinking can help increase adoption rates.

Number of IPM outcomes: Table 5 shows the number of outcomes of IPM implementation. Reductions in pest populations, increased yields, and economic returns demonstrated tangible benefits from integrated pest management strategies, providing valuable feedback for recommendations.

These tables collectively offer a comprehensive understanding of crop-pest dynamics, the ecological context, economic implications, stakeholder perspectives, and the quantitative outcomes of implementing IPM strategies. The interpretation of these tables contributes to informed decision-making in agricultural practices, aiding in the development of sustainable and economically viable pest management strategies.

Interpretation of the results

The presented tables collectively provided a nuanced insight into the dynamics of crop-pest interactions and the efficacy of IPM strategies. The ecological measurements highlighted the variability in environmental factors across different experimental plots, influencing pest populations and interactions. The economic injury levels and yield metrics underscore the economic implications of pest damage, emphasizing the need for a balanced approach to pest management. The positive responses from stakeholders in the IPM evaluation interviews suggest a willingness to adopt integrated strategies, further supporting the potential benefits of such approaches. This is in agreement with Jackson (2008) who noted that IPM) is a multifaceted approach that combines biological, cultural, and artificial practices to effectively control pests and achieve production objectives.

The practical applications of these results are extensive, particularly for farmers, agronomists, and policymakers involved in agricultural practices. The data generated from the economic injury levels and yield metrics could guide farmers in making informed decisions on when and how to implement pest control measures, optimizing resource allocation and minimizing economic losses. Similarly, Rincon et al. (2019) reported that disease incidence should be used to calculate the Economic Injury Level (EIL) for potato yellow vein disease management, as direct insect injury does not affect yield.

Stakeholder perceptions, as shown in the interviews, may inform extension programs and educational initiatives aimed at promoting the adoption of sustainable pest management practices, particularly those involving IPM.

Several factors contribute to the observed results. The ecological measurements reflect the influence of environmental variables on pest dynamics, showcasing the importance of biodiversity, soil health, and climate in shaping crop-pest interactions. Tajudeen et al. (2022) documented that climate change negatively impacts crop productivity in Lagos, Nigeria, by decreasing crop yield, soil fertility, limiting soil water availability, increasing soil erosion, and contributing to the spread of pests. The positive outcomes in the IPM evaluation metrics highlight the effectiveness of integrated approaches, suggesting that factors such as the choice of pest control methods and their integration with existing farming practices play a pivotal role in achieving successful outcomes.

Implications of the findings: The findings revealed significant implications for sustainable agriculture. The positive perceptions toward IPM indicated a growing recognition of its benefits, fostering a shift towards more ecologically friendly and economically viable pest management practices. The economic injury levels offer a practical metrics for farmers to assess the economic viability of their pest control measures, providing a basis for decision-making that aligns with both economic and environmental sustainability goals. Similar view was also expressed by Flöhr et al. (2018).

Identification of limitations or sources of error: While the results provided valuable insights, it is essential to acknowledge the limitations inherent in the study. The experimental setup and procedure, while carefully designed, could not have fully captured the complexity of every agricultural systems. Factors such as variations in local conditions, unforeseen environmental fluctuations, and the potential for confounding variables may have introduced uncertainties. Additionally, the qualitative data from interviews was subjective and might have been influenced by respondent biases or varying interpretations of IPM concepts.

In summary, this investigation into crop-pest dynamics and variations in economic injury levels has yielded valuable insights into the intricate relationships within agricultural ecosystems. The ecological measurements revealed the diversity in environmental factors across experimental plots, influencing pest populations and interactions. Economic injury levels and yield metrics demonstrated the economic consequences of pest damage, emphasizing the importance of a balanced approach to pest management. The positive stakeholder perceptions towards IPM further supported the potential benefits of such strategies in fostering sustainable agricultural practices.

Contributions to existing knowledge: This study contributes significantly to the existing body of knowledge by integrating ecological and economic approaches to crop and pest development. The tables provided a detailed overview of the interactions between environmental factors, economic considerations, and stakeholder perceptions. IPM models, combined with qualitative and quantitative analysis, enhance understanding of sustainable pest management practices. Findings build on existing literature to provide a holistic approach towards emphasizing the practical implications of balancing ecosystem health and economic growth in agriculture. The importance of this research lies in its ability to inform agricultural practices and guide towards sustainability. By clarifying the economic consequences of pest management and emphasizing the benefits of integrated approaches, the study highlights the importance of adopting pest management strategies emphasizing all the solutions, which is of particular importance in light of global food security and the need for resilient agricultural systems that can withstand increasing pressures from pests and environmental change. Future research in this area could further examine the specific mechanisms by which environmental factors influence crop-insect interactions. In addition to evaluating the role of different pest control practices in the IPM strategies to gain a deeper understanding of their effectiveness and efficiency, a longitudinal study assessing the impact of IPM taking effects on the economy and the environment in the long run will contribute to a lot more comprehensive understanding of sustainability in agriculture.

CONCLUSION

This study explores the complex dynamics between crops and pests, as well as the variability in economic injury thresholds across diverse agricultural environments. It uses a comprehensive mixed-methods approach to integrate ecological and economic perspectives, providing a holistic understanding of these critical factors in sustainable agriculture. The ecological measurements reveal the influence of environmental factors such as temperature, precipitation, soil health, and biodiversity indices on pest populations and their interactions with crops. Economic injury levels and yield metrics demonstrate the tangible economic consequences of pest damage, underscoring the importance of a balanced approach to pest management that considers both ecological and economic implications.

The study's findings highlight the positive perception of stakeholders, including farmers, agronomists, and experts, towards Integrated Pest Management (IPM) strategies. The qualitative data from interviews reflects a growing recognition of the practical benefits and potential of IPM in fostering sustainable agricultural practices. The quantitative evaluation of IPM outcomes showcases reductions in pest populations, improved crop yields, and economic benefits across various experimental plots.

The study's contributions are multifaceted. First, it bridges the gap in literature by integrating economic perspectives into the analysis of crop-pest dynamics, which have traditionally focused on ecological and environmental factors. Second, the mixed-methods approach, combining ecological measurements, economic analyses, stakeholder perceptions, and quantitative evaluations of IPM strategies, offers a holistic framework for understanding the intricate relationships within agricultural ecosystems. Third, the findings on stakeholder perceptions and the quantitative evaluation of IPM outcomes contribute to the growing body of evidence supporting the efficacy of integrated approaches in pest management.

In conclusion, this investigation into crop-pest dynamics and variability in economic injury thresholds has made significant strides in advancing our understanding of these critical issues in agriculture. The findings and recommendations presented serve as a foundation for future research efforts and practical applications in the field.

Suggestions for future research: Based on the insights from this study, future research efforts should focus on developing on-farm recommendations for farmers, comparative studies under different agricultural conditions considering variations in climate, soil type and crop diversity into and emerging technologies, such as precision farming and remote integration sensing. Furthermore, collaborative efforts among researchers, policymakers, and farmers can ensure that research findings play a role in practical, grassroots solutions. In conclusion, this study has contributed to a nuanced perspective in the discourse on crop-pest management, and highlights the need for a holistic sustainable approach to pest management. The findings and recommendations presented here provide a basis for future research and inform efforts to build resilience and environmentally sustainable agricultural systems.

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Ecological Assessment of the Wood Vegetation of Rashad District, Nuba Mountains, Sudan

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ABSTRACT

The objective of the present study is to analyze the phytosociological characteristics and the diversity patterns of woody plants in Rashad district. The study was conducted in selected 6 vegetation sites. Important Value Index (IVI) and density were used to estimate the phytosociological characteristics, the Shannon index to measure the plant diversity and the Pielou index for species equitability. During the study period, a total of 64 species, representing 39 genera from 17 families, were recorded. The phytosociological characteristics revealed that *Dichrostachys cinerea, Balanites aegyptiaca* and *Vachellia seyal* var. *seyal* dominated woody species in sites of clay plains with IVI values 180.1, 128 and 116.4 respectively. While *Terminalia leiocarpa, Boswellia papyrifera* and *Adenium obesum* dominated woody species in hilly sites of rocky soil with IVI values (45.76), (45.38) and (43.97) respectively. The distribution pattern revealed that 54% species showed aggregated distribution, while 46% were randomly distributed. The highest density was 766 stem/ha recorded in site 6. Species richness varied through different sites; the highest number of species was 44, recorded in community 4. The highest values of Shannon diversity index and equitability index were in community 4. The highest similarity was recorded between site 3 and site 4 (50.9%) and the lowest (17.9%) between site 1 and site 2. Biodiversity indices relatively increased with increment of elevation.

Keywords: Beverages vegetation, Diversity, Equitability, Species, Plants, Taxonomy

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INTRODUCTION

The natural vegetation is one of the renewable natural resources, which includes natural forests and natural pasture, both plays important role for rural communities. It provides fuel, famine food, medicines, building materials, gums and fodders; in addition to its environmental importance.

The Nuba Mountains is located in South Kordofan State, which bordered the Republic of South Sudan. It is a mountainous region, with topographic features dominated by isolated mountains that are dissected by seasonal *KHORS*. In addition to lowland plains, the region consists of some high plateaus, the greatest one is Rashad massif. Eastern Nuba Mountains Region selected for the present study exhibits wide topographical variations; which are reflected in vegetation diversity. There are no available detailed studies on the floristic composition and vegetation status of the proposed area. The vegetation of this region like other parts of the Sudan is expected to be affected by the seventies and eighties drought periods, in-addition to the expanded agricultural practices and grazing.

Andrews (1948) classified the study area into two vegetation divisions as follow: *Acacia* tall grass forest where *Acacia* species are dominant in addition to *Terminalia* spp., *Combretum* spp., *Guiera senegalensis*, and *Tamarindus indica*. Smith, (1949) classified the area as *Acacia* tall grass country similar to that of (Andrews, 1948) with slight modification. Harrison and Jackson, (1958), classified the area as low rainfall woodland savannah on clay where *Acacia mellifera* thorn-land on hill soil formed *in situ* associated with *Commiphora africana* and *Boscia senegalensis* and as special areas of low rainfall wood land savanna under Hill catena's. These hills have a characteristic vegetation of their own generally much moister in character than surrounding plain and showing erosion catena development. Between the groups forming the Nuba Mountains are extensive plains of dark cracking clays carrying *Vachellia seyal* - *Balanites aegyptiaca* savanna.

This study is aimed at assessing the vegetation composition and forecasting the future behavior of plant composition and regeneration power through studying natural regeneration in the study area.

MATERIAL AND METHODS

Description of the study area

The study area is located in the northern part of eastern Nuba Mountains of South Kordofan State and including two localities (Rashad and Alabassia), extending from latitude 11° 33` to 12° 33` N and from longitude 31°08` to 31° 18` E (Fig. 1). Most of the area under study is covered by scattered isolated hills and it is dissected by many seasonal watercourses (*KHORS*). Study area occupies a total area of 7872 km^2 (UNDP, 2003). The study area belongs to low rainfall woodland savanna (Harrison and Jackson, 1958).

Vegetation sampling

Six vegetation communities were selected, based on observed variations in vegetation types, topographical feature and soil types to represent most of the study area (Table 1). For vegetation assessment within the natural stands 70 circular 0.1 ha (17.84m in radius) sample plots modified from Adam and Eltayeb (2008). 14 transect were made to cover the whole study area. Along each transect 5 circular 0.1 plot were conducted for studying trees and shrubs. The first plot was established randomly, the number of trees and shrubs species and the number of individual of each species per/plot were counted.

Data analysis

Phytosociological analysis

Species encountered in each quadrate were counted. From count data, density (D), abundance (A), frequency (F %), relative density (RD %), relative abundance (RA %), relative frequency (RF %) and importance value index (IVI) were calculated for each species in each site using the following formulas as used by Dangoli and Shivakoti (2001) and Chaudhry et al. (2006).

$$\text{Density (D)} = \frac{\text{number of plant of a certain species}}{\text{Total area sampled}}$$

$$\text{Relative density (RD \%)} = \frac{\text{Density of species}}{\text{Total density of all species}} \text{X100}$$

$$\text{Abundance (A)} = \frac{\text{Total number of individual}}{\text{No. of quadrate where species occur}}$$

$$\text{Relative abundance(RA\%)} = \frac{\text{Abundance of species}}{\text{Tatal abundance of all species}} \text{ x 100}$$

$$\text{Frequency (F\%)} = \frac{\text{No.of quadrate where species occur}}{\text{Total numbers of quadrate}} \text{ x 100}$$

$$\text{Relative frequency (RF\%)} = \frac{\text{frequency of species}}{\text{Total frequency of all species}}$$

Importance value index (IVI) = RD% + RA% + RF%

Diversity indices

Species richness was determined as the total number of species present in the studied site. The Shannon diversity index applied to estimate woody plant species diversity along the study area (Shannon, 1949). This index was calculated by the equation Hs = -Σpi In pi. Where, pi is the proportion of individuals found in the ith species and 'In' denotes the natural logarithm. Pielou index used for estimation of species evenness (E) after (Pielou, 1966). This index was calculated by the equation E = H/lnS. Where: H' is the Shannon-Wiener diversity measure, S is Number of species. Species distribution pattern test and Comparisons of woody plant species composition between different plots were estimated using single linkage cluster analysis based on Jaccard similarity, Biodiversity Pro version 2 (Mc Aleece, 1998).

Table 1: Selected Vegetation Communities

community	Area	Latitude	Longitude	Elevation	Topography
1	Um fakareen area	12^{o} 33` N	31^{o} 18` E	500 m	Cracking clay plain
2	AlAbassia area	12^{o} 10` N- 11$^{o}$ 57` N	31^{o} 15` E- 31$^{o}$ 12` E	826.5 m	Hill (Rocky soil)
3	Rashad area	11^{o} 52` N-11$^{o}$ 49` N	31^{o} 08` E- 31$^{o}$ 03` E	871.5 m	Hill (Rocky soil)
4	South Rashad area	11^{o} 45` N-11$^{o}$ 43` N	31^{o} 02` E- 31$^{o}$03` E	722.5 m	Hill (Rocky soil)
5	Tandek area	11^{o} 42` N	31^{o}02` E	695 m	Cracking clay plain
6	Dibekkir area	11^{o} 33` N	31^{o}08` E	618 m	Cracking clay plain

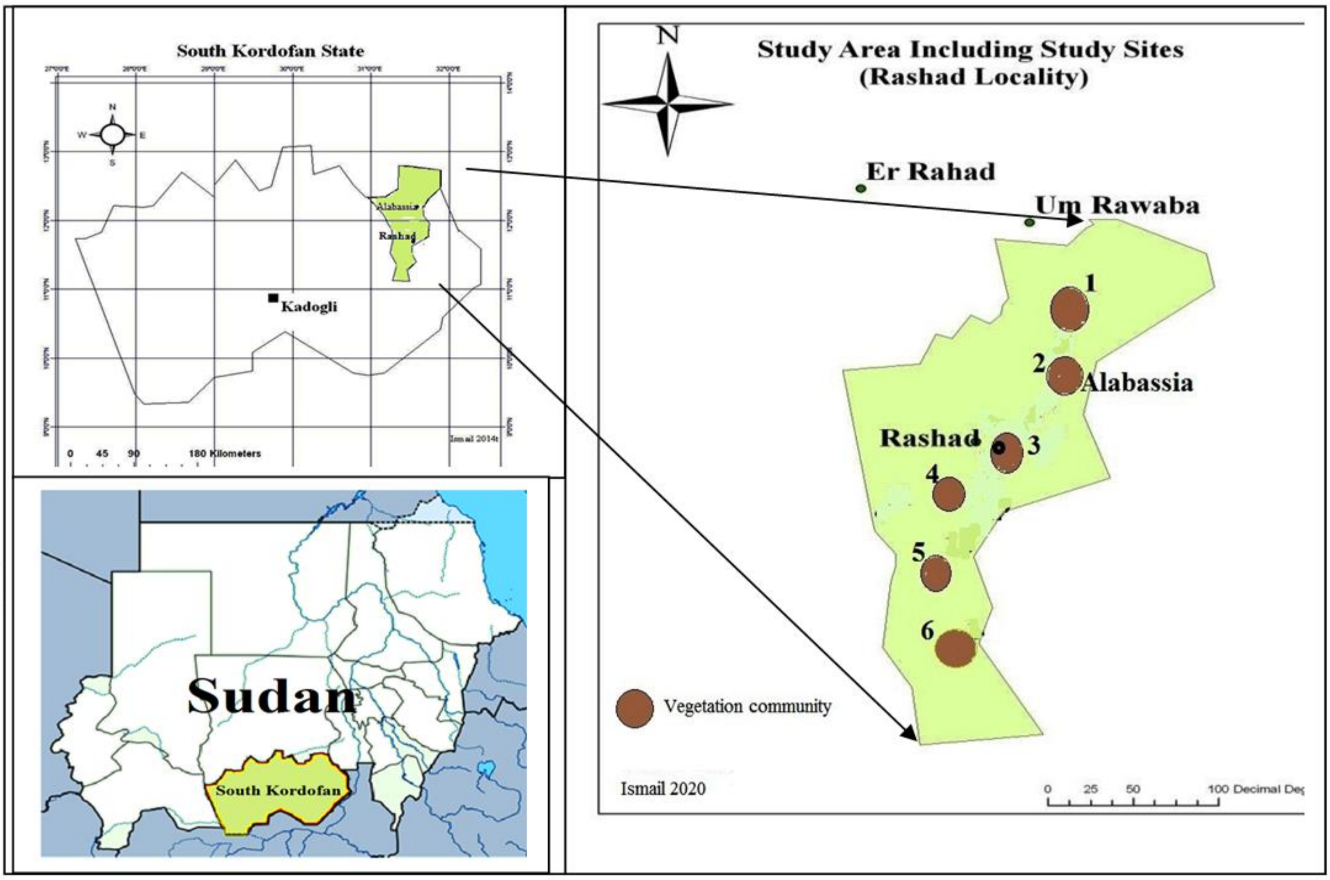


Figure 1: Map of the Study Area

RESULTS

Taxonomy

A total of 64 species, representing 39 genera from 17 families, were recorded from the studied sample plots. Fabaceae was the dominant family with 15 species, followed by Combretaceae (8), Malvaceae (6), Moraceae and Rubiaceae (5 species each), Anacardiaceae and Capparaceae (4 species each), while the other 9 families were represented by less than 3 species (Table 2).

Dominance

The topography and soil types play an important role in dominance and distribution of species. The dominance of species was assigned based on the calculated IVI values. *Dichrostachys cinerea* which dominated community 6 that located in clay plain, was recorded a highest value of IVI (180.1) in the study area. *Balanites aegyptiaca* dominated community 5 in clay soil with IVI value (128) where the. *Acacia seyal* var. *seyal* dominated community 1which described as clay plain with IVI value with (116.4). While community (4) in rocky soil was dominated by more than on species which are *Terminalia leiocarpa, Boswellia papyrifera* and *Adenium obesum* with IVI values (45.76), (45.38) and (43.97) respectively. *Combretum glutinosum* dominated community (3) with IVI value (31.32) and community (2) was dominated with *commiphora africana* and *Balanites aegyptiaca* with IVI (36.76) and (27.52) respectively. The above mention results relatively agreed to distribution map of Harrison and Jackson (1958).

Density

The highest density of woody plants was recorded in community 6 (766 plant/ha.), followed by community 3 (262 plants /m^2), while community 5 showed the lowest density (48 plant /ha.) (Fig. 2). *Dichrostachys cinerea* in community 6 showed the highest relative density (85.12%) of woody plants in whole the study area, followed by *Balanites aegyptiaca* in community 5and *Vachellia seyal* var. *seyal* in community 1 with relative density (58.33%) and (54.4%) respectively, *Vachellia oerfota* with relative density (29.8%) and *Ziziphus spina-christi* (20.83%) in community all above mentioned communities located in clay plains. But in communities of hilly sites, *Boswellia papyrifera* in community 4 showed highest relative density (25.20%) followed by *Terminalia leiocarpa* (23.09%) in the same community, and *Commiphora africana* (17.86%) in community 2. While the rest species their relative density ranging between 0.38% -11.02 percent (Table 2).

Species Distribution Patterns

Distribution of plant species was assessed and result revealed that 29 species (47%) were randomly distributed and 33 species (53%) were aggregated (Table 2). It is Obviously from the above results that most (53%) of the species were aggregately distributed this may due to that their regeneration close to seed sources, vegetative regeneration or the occurrence in safe site‟ (Augspurger, 1984), or on traces of animal movement or in catchment are especially the case of *Dichrostachys cinerea.*While (47%) of the species encountered during the sampling were randomly distributed and this indicates that the environment in which these plant species grow is homogeneous and has many factors acting on the population (Ewusie, 1980), these factors includes seed dispersal and anthropogenic factors.

Species richness and diversity indices

The composition among the different communities in terms of species richness showed that the highest species diversity was observed in community 4 (44 species) in hilly sites,, while the least values of richness (6 species) was observed in communities 1 and 5, both located in clay plains.

The highest Shannon diversity index was 3.05 in community 4, followed by 2.88 in community 2 and 2.74 in community 3, whereas the least Shannon diversity index was 0.69 in community 6. The highest species equitability index (J) was recorded in community 2 was (0.806), whereas the least evenness index was 0.302 in community 6 (Fig. 3).

DISCUSSION

Overall population species diversity index, evenness, richness and density of all species through different communities increased with an increment of elevation and also affected by soil type. The quantitative inventory of plant species diversity showed considerable diversification in vegetation component throughout different communities.

The lowest elevations of clay plains (communities I, 5 and 6) are characterized by the fast growing species, specially *Vachellia seyal*, *Senegalia senegal* and *Senegalia mellifera* in community one, and *Balanites aegyptiaca, Vachellia nilotica* and *Vachellia seyal* in community two, while community three is characterized by the dominance of *Dichrstachys cinnerea and Vachellia seyal.* These communities agreed with zone of *Vachellia seyal* – Balanities in cracking clay plains of low rainfall woodland savanna which stated by Harrison and Jackson, (1958). While the other three Communities (2, 3 &4) are characterized by the species of hill catena`s which fall under the special areas of the low rainfall woodland savanna zone, such as *Sterculia setigera, Sclerocarya birrea, Strychnos innocua* in addition to other savanna tree species, (Harrison and Jackson, 1958).

Fabaceae, Combretaceae, Malvaceae, Moraceae and Rubiaceae are well represented in all six communities. On the other hand the number of species included by Fabaceae, Combretaceae, Malvaceae increased in hilly communities (2, 3 and 4), with the increment of elevation and the dominance of gravelly soil.

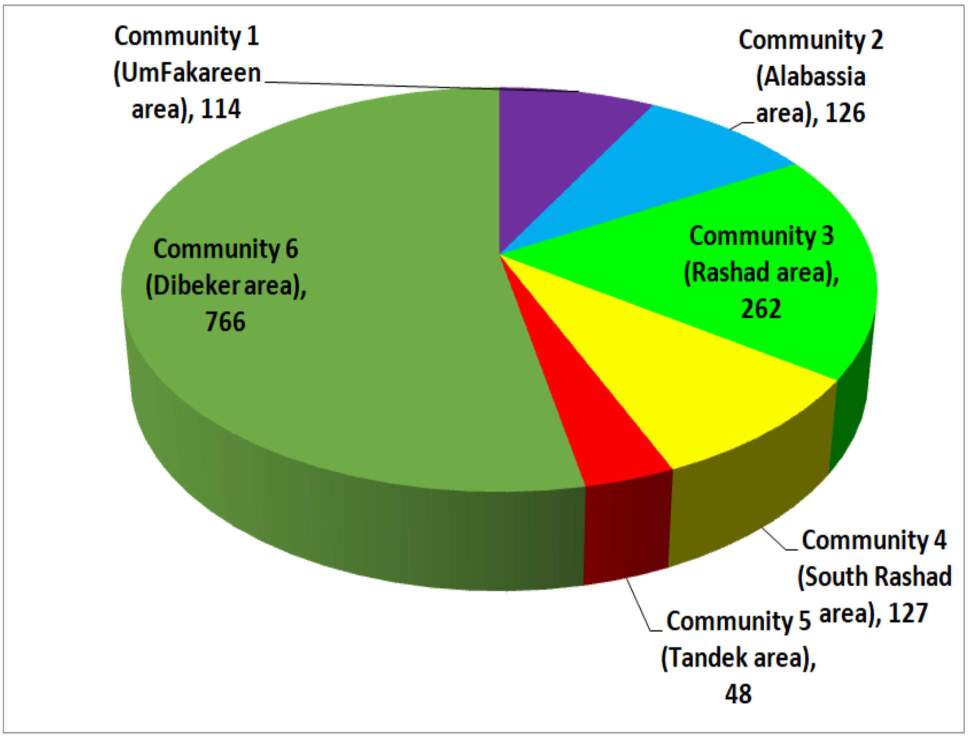
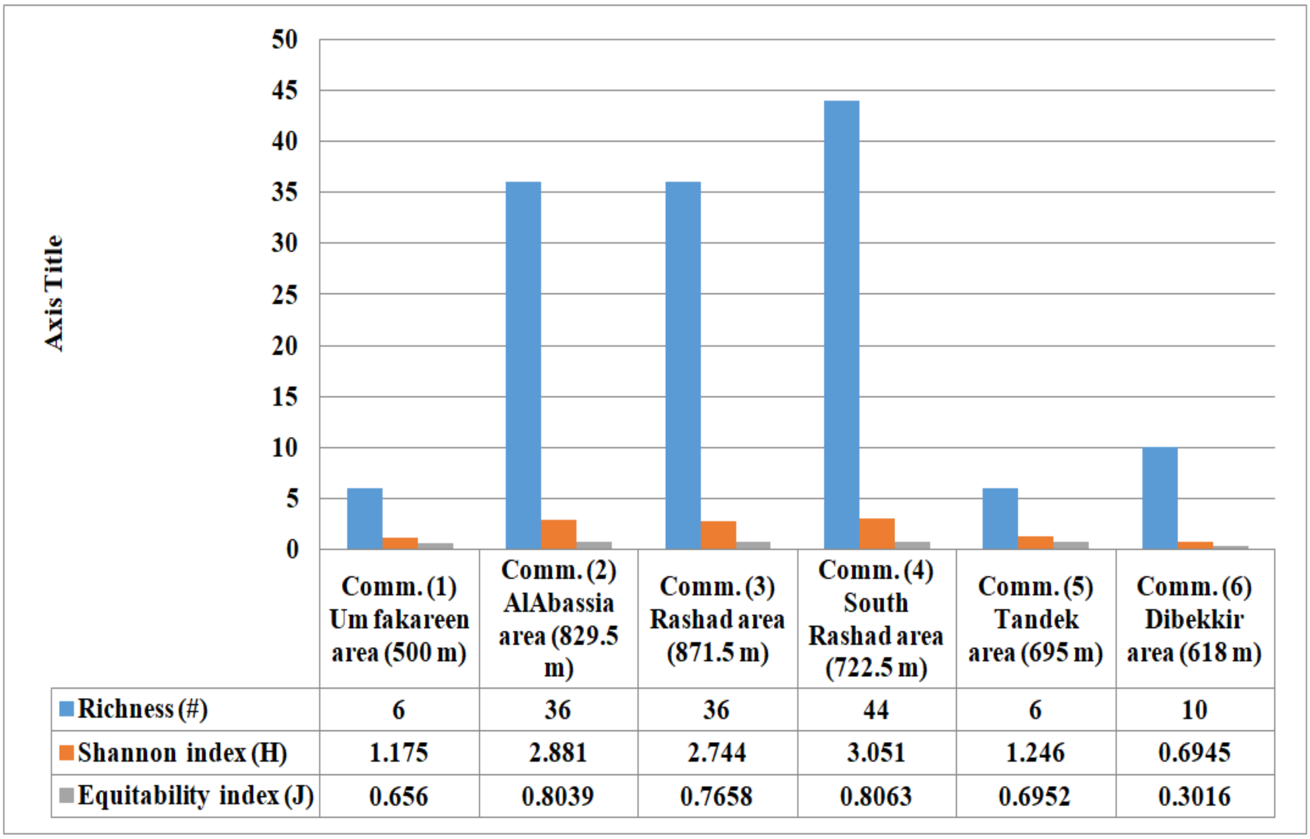


Figure 2: Showed stem density (plant/ha.)



	Comm. (1) Um fakareen area (500 m)	Comm. (2) AlAbassia area (829.5 m)	Comm. (3) Rashad area (871.5 m)	Comm. (4) South Rashad area (722.5 m)	Comm. (5) Tandek area (695 m)	Comm. (6) Dibekkir area (618 m)
■ Richness (#)	6	36	36	44	6	10
■ Shannon index (H)	1.175	2.881	2.744	3.051	1.246	0.6945
■ Equitability index (J)	0.656	0.8039	0.7658	0.8063	0.6952	0.3016

Figure 3: Showed Richness and Diversity indices

The increment of plant species diversity in communities of higher elevation may attribute to different ecological factors such as differences in temperature between different elevations and differentiation of soils. The effect of elevation gradient in the species richness pattern is commonly explained by similar factors to the altitudinal gradient such as climatic factors, productivity, and other energy-related factors, (Richerson and Lam, 1980; Lomolino, 2001). Lomolino (2001) pointed out that many components of climate and environmental factors (e.g: temperature, precipitation, seasonality and disturbance regime) vary along elevation gradients and ultimately create the variation in species richness. Elevation gradients create varied climates, along with resultant soil differentiation; promote the diversification of plant species (Brown, 2001; Lomolino, 2001). In addition to intensive human activities such as shifting cultivation and collection of fire wood in lower elevations (community I, 5 & 6), decreased the plant species diversity. Human activities largely impact the natural rate of change in biodiversity by influencing species invasion, displacement and extinction rates, (Sala *et al,* 2000). Accordingly the difficulty of accessing the higher elevations, play an important role for conserving species diversity in higher elevations (communities 2, 3 & 4).

It is obviously that all communities located in sites of dark cracking clay soil and of low elevations are dominated by one species; while the other communities of hilly soil and high elevation are dominated by several species; these findings agreed with the fact that the dominance of only one or few species in trees and shrubs layer resulting in the decrease of the values of diversity indices in clay plains of low elevations; on the other hand dominance of several species resulting in the increment of the values of diversity indices in mountainous sites of high elevation (Ismail and ElAwad, 2017).

The multiple-similarity measures indicated that the higher percentage of similarity (more than 45%) was recorded between Community 3 and community 4 (Figure 4). this might be explained by the fact that these plots have similar altitudes and environment characteristics.

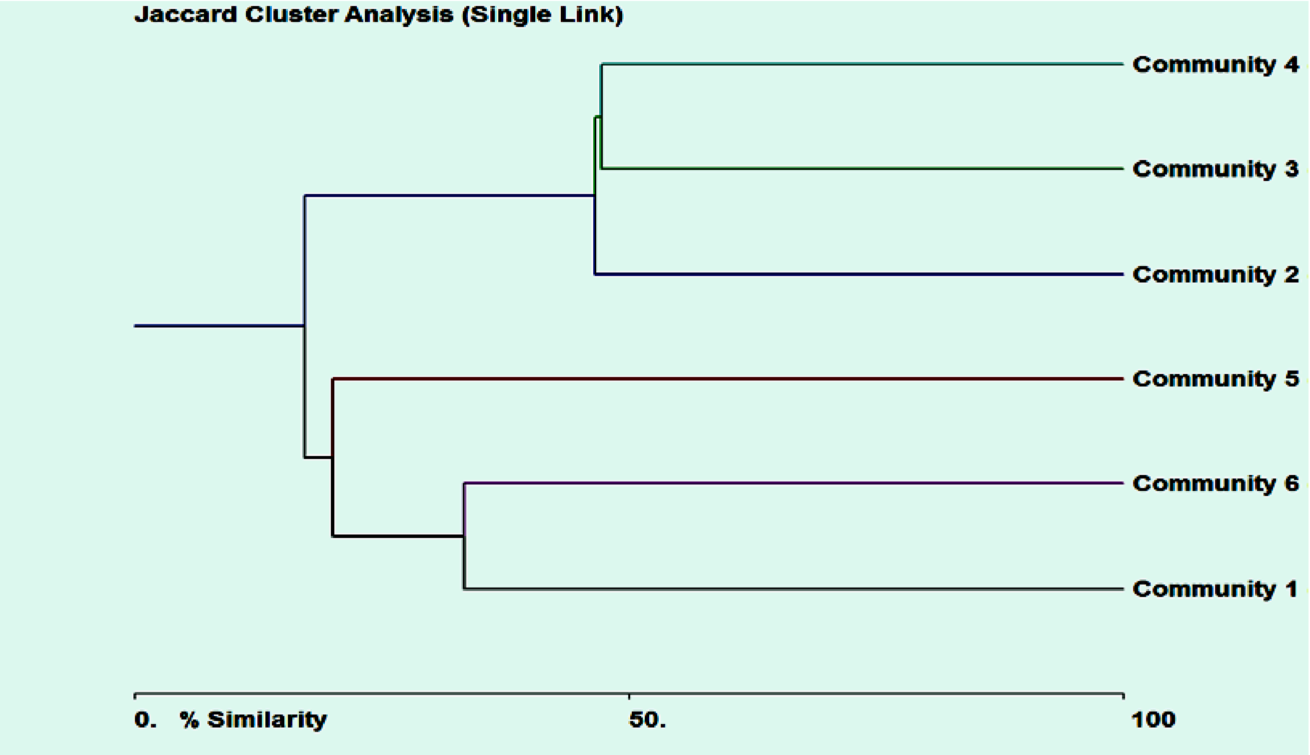


Figure 4: similarity between different communities

CONCLOSION

The quantitative inventory of plant species diversity showed that a considerable variation in vegetation components throughout different communities.The communities of lowest elevation and clay plains (1, 5, 6) is characterized by the fast grown species of Acacia seyal –Balanites in dark cracking clay plain sub-zone of low rainfall woodland savanna, such as *Vachellia seyal, Senegalia mellifera, Senegalia senegal, Balanites aegyptiaca* and *Dichrstachys cinnarea.* While the communities of higher elevations (2, 3 & 4) characterized by the species of high rainfall woodland savanna zone, such as *Sterculia setigera, Sclerocarya birrea, Strychnos innocua*in addition to other savannah tree species.

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Table 2: Analysis of Phytosociological Parameters and Distribution Pattern Along Six Vegetation Communities

Family	**Species**	**Vernacular name**	Canopy layer												
			Comm. 1		**Comm. 2**		**Comm. 3**		**Comm. 4**		**Comm. 5**		**Comm. 6**		**Distribution Pattern**
			Rd	**IVI**	**Rd**	**IVI**	**Rd**	**IVI**	**Rd**	**IVI**	**Rd**	**IVI**	**Rd**	**IVI**	
Zygophyllaceae	*Balanites aegyptiaca* (L.) Delile	Hijlij	2.26	25.4	13.095	27.52	1.91	7.94			58.33	128.7	3.66	20.62	Aggregated
Fabaceae Subfamily Caesalpinoideae	*Bauhinia rufescens* Lam.	Kulkul					1.72	6.79			4.17	22.69			Aggregated
	Bauhinia reticulata DC.	Kharoub			0.4	2.91	0.76	3.25							Aggregated
	Tamarindus indica L.	Aradeib			0.40	2.90	0.76	3.25	1.05	5.25					Random
Subfamily Mimosoideae	*Vachellia gerrardii* (Benth.) P.J.H.Hurter	Salgam					0.19	1.43	1.31	5.68			2.6	7.61	Random
	Senegalia mellifera (Vahl) Seigler & Ebinger.	Kitir	7.02	31.8	12.3	25.77	0.76	2.77					2.6	7.61	Aggregated
	Vachellia nilotica subsp. *adstringens* (Schumach.) Kyal & Boatwr.	Sunt									8.33	34.7			Random
	Vachellia oerfota (Forssk.) Kyal & Boatwr.	Laot	29.8	95.11	1.98	7.39							2.35	15.3	Aggregated
	Senegalia polyacantha (Willd.) Seigler & Ebinger.	Kakamut			0.40	2.90									Random
	Senegalia senegal (L.) Britton.	Hashab			1.98	7.39	1.15	4.92	2.62	9.19			1.57	15.4	Random
	Vachellia seyal (Del.) P.J.H.Hurter	Talih	54.4	116.4			0.38	2.39	0.53	3.38			3.66	23.1	Aggregated
	Acacia sieberiana (DC.) Kyal & Boatwr.	Kuk					6.11	14.52	1.05	5.25					Aggregated
	Albizia amara	Arad			0.79	4.22	0.38	2.10	2.10	6.76	4.17	22.69			Random

	subsp.sericocephala (Benth.) Brenan.														
	Albizia anthelmintica (A. Rich.) Brongn	Um-Takirna			1.98	7.39	0.38	2.39	1.05	5.41					Aggregated
	Dichrostachys cinerea (L.)White & Arn.	Kadad			0.79	4.89	0.76	3.69	0.53	3.38			85.12	180.1	Aggregated
	Anonychium africanum (Guill. & Perr.) C.E.Hughes & G.P.Lewis	Abu-Suruj					0.38	2.10							Random
Subfamily papilionoideae	*Dalbergia melanoxylon* Guill. & Perr.	Babanos			3.18	10.31	1.53	6.11	4.72	13.29					Aggregated
	Erythrina abyssinica DC.	Hab Elaroos			0.79	4.22	0.19	1.43	0.53	3.38					Random
	Mundulea sericea (Willd.) A. Chev.	Abu-Galinga					0.19	18.46							Aggregated
Rhamnaceae	*Ziziphus abyssinica* Hochst. ex A. Rich.	Nabag Elfeel					0.38	1.62	1.57	7.13					Aggregated
	Ziziphus spina-christi (L.) Wild..	Sidir			2.38	9.48	1.91	7.94	1.57	6.53	20.83	68.98	2.35	20.34	Random
Moraceae	*Ficus abutilifolia* Miq.	Gumaiz					0.19	1.43							Random
	Ficus glumosa Del.	Gumaiz (Umbalil)			0.79	4.22	0.38	2.39							Random
	Ficus platyphylla Del.	Gumaiz					0.19	1.43							Random
	Ficus populifolia Vahl.	Gumaiz			0.4	2.91	0.57	2.77							Random
	Ficus thonningii Blume.	Gumaiz (Hadana)							0.53	3.38					Random
Euphorbiaceae Subfamily Euphobioideae	*Euphorbia candelabrum* Welw. ex Hiern	Zagoom					1.15	4.92							Aggregated
Passifloraceae Subfamily Passifloroideae	*Adenia venenata* Forssk.				0.40	2.90									Random

Combretaceae	*Terminalia leiocarpa* (DC.) Baill.	Sahab			5.16	14.11	3.05	8.40	23.09	45.76					Aggregated
	Combretum aculeatum Vent.	Siheit			9.13	19.86	4.58	16.85							Aggregated
	Combretum collinum subsp. *binderianum* (Kotschy) Okafa.	Habeel					0.38	2.10							Aggregated
	Combretum glutinosum Perr. ex DC.	Habeel			1.59	6.45	17.37	31.32	2.10	9.51					Aggregated
	Combretum hartmannianum Schwein f. Beitr.	Habeel							0.53	3.38			0.52	9.37	Random
	Guiera senegalensis J. F. Gmel.	Ghibeish					3.82	9.30							Random
	Terminalia brownii Fresen	Subagh			1.98	7.64	1.91	6.16							Aggregated
	Terminalia laxiflora Engl.	Daroat					0.19	1.43							Random
Burseraceae	*Boswellia papyrifera* Hochst.	Taragtrag - Luban			0.40	2.90			25.20	45.38					Aggregated
	Commiphora africana (A. Rich) Engl.	Gaffal			17.86	36.76	2.29	6.50	1.05	5.25					Aggregated
Anacardiaceae	*Lannea fruticosa* Engl.	layon			1.59	6.45			1.05	5.25					Aggregated
	Lannea humilis Engl.	layon											2.6	7.61	Random
	Lannea schimperi Engl.	Layon (Mileis)					1.15	5.54	0.53	3.38					Aggregated
	Sclerocarya birrea Hochst.	Himeid			0.79	4.22	0.57	3.34	1.57	7.13					Random
Sapindaceae	*Allophylus africanus* P. Beauv.				1.59	6.60	4.77	11.83							Aggregated
Meliaceae	*Khaya senegalensis* A. Juss.	Mahogani					0.19	1.43	3.15	10.36					Aggregated

	Trichilia emetica Vahl.	Dimso					0.57	2.77							Random
Malvaceae Subfamily Bombacoideae	*Adansonia digitata* L.	tabaldi			0.40	2.90									Random
Malvaceae Subfamily Grewiodeae	*Grewia flavescens* Juss.	Khlekhsan					3.63	10.79	5.77	15.31					Aggregated
	Grewia mollis Juss.	Basham					1.91	7.29							Aggregated
	Grewia tenax (Forsk.) Fiori.	Gudeim	1.75	14.2	3.57	11.1	0.19	1.43	1.05	5.25	4.17	22.69			Aggregated
	Grewia villosa Willd.	Gregdan			2.38	9.35	1.34	5.23	1.05	5.41					Aggregated
Subfamily Sterculiodeae	*Sterculia setigera* Del.	Tartar			5.95	16.87	0.38	2.39							Aggregated
Capparaceae	*Boscia angustifolia* A. Rich.	Sarah, Sireih			0.4	2.91	4.01	14.84							Aggregated
	Boscia senegalensis Lam.	Mikheit,	-	-	0.79	4.89									Random
	Cadaba rotundifolia Forssk.	Kurmut	1.75	14.2											Random
	Capparis tomentosa Lam.				0.40	2.90	0.19	1.43							Random
Ebenaceae	*Diospyros mespiliformis* Hochst. ex A.DC.	Joghan					0.38	2.39							Aggregated
Rubiaceae Subfamily Cinchonoideae	*Nauclea latifolia* Sm.	Karmadoda					0.38	2.10							Random
Subfamily Ixoroideae	*Catunaregam nilotica* (Stapf.) Tirveng.	Shigart Elmarfaeen			0.79	4.22	2.29	6.69	1.05	5.41					Aggregated
	Feretia apodanthera Del.	Shegart ElShai					2.29	8.81	2.10	7.81					Aggregated
	Meyna tetraphylla (Schweinf. ex Hiern) Robyns.	Simeim							0.53	3.38					Random

	Vangueria madagascariensis J.F.Gmel.	Kirkir			0.79	4.22									Random
Loganiaceae	*Strychnos innocua* Del.	Um Bikhesa					0.19	1.43	11.02	43.97					Random
Apocynoideae Subfamily Apocynoideae	*Adenium obesum* (Forssk.) Roem & Schult.	Shigart Elsim			2.38	8.31	0.76	3.25							Aggregated

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Bamboo Cultivation as a Sustainable Agroforestry Practice: Balancing Environmental Conservation and Economic Benefits in Nigeria

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ABSTRACT

This study examined bamboo cultivation in different ecological zones in Nigeria with the objective of assessing its economic viability, ecological benefits, and associated challenges. Objectives included identifying the characteristics of the experimental zones, appraising bamboo tree parameters, assessing the economic benefits as well as the ecological benefits, and identifying constraints and opportunities. Methodologically, experimental sites were categorized based on region, agro-climatic zone, bamboo species, soil type, and cultivation practices. Measurement parameters encompassed soil pH, organic matter, nutrient levels, bamboo height, diameter, biomass accumulation, and environmental variables, monitored using specific instruments. There were variations in data across regions: the North emphasizing traditional uses, the South-East focusing on commercial applications, and the South-West adopting an integrated approach. Economic analysis indicated varying income generation, job creation, and value addition, with the South-East demonstrating the highest economic returns. Ecological benefits included soil conservation, carbon sequestration, and biodiversity enhancement, varying across the various regions. Recommendations involve regular validation, stakeholder collaboration, policy development, market and infrastructure investments, financial support, technical training programs, land tenure policies, and continuous monitoring. The paper concludes that bamboo cultivation holds considerable potential in Nigeria for sustainable growth, economic development, and environmental resilience.

Keywords: Agroforestry, Bamboo, Carbon sequestration, Conservation, Soil health, Sustainable agriculture

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INTRODUCTION

In the course of sustainable agroforestry practices in Nigeria, bamboo plantations stand out as a promising solution offering a minimal approach considering environmental protection and economic benefits. Environmental benefits include the role of bamboo in supporting ecosystems. Its dense vegetation provides habitat for a variety of species and contributes greatly to the ecological balance. Furthermore, the dense roots of bamboo trees play an important role in controlling soil erosion, providing stable slopes, and reducing the risk of landslides, thus improving soil quality and buffering environmental edges (Shettima et al. 2017; Gidon and Sahoo, 2020; Xiao et al. 2021). Furthermore, bamboo's unique carbon storage capacity is consistent with Nigeria's commitment to address climate change, making it a valuable contributor to carbon sequestration efforts (Nath et al. 2015; Sohel et al. 2015).

As bamboo cultivation increases sustainable agriculture, it can provide useful resources to ensure food security and promote rural development. Furthermore, the research on bamboo cultivation in Nigeria has practical and theoretical implications. In practical terms, the findings can guide policymakers, agricultural practitioners, and environmentalists to develop strategies and policies that promote sustainable bamboo agriculture. In theory, this research could enhance our understanding of the complex relationship between agriculture, ecology, and the economy, especially in the context of developing countries such as Nigeria (Lu et al. 2018). This study of bamboo agriculture in Nigeria goes beyond its immediate context, providing a lens through which we can explore and address the wider challenges and opportunities in sustainable, environmentally friendly agriculture protection and rural development (Atanda, 2015; Molua and Emagbetere, 2005; Gideon, 2018).

Bamboo cultivation provides income and employment opportunities. Research has shown that the economic benefits of bamboo can be reflected in products such as furniture, handicrafts, and construction materials, which, especially in rural production, can be translated into sustainable livelihood development through bamboo farming consistently to stimulate employment and poverty alleviation, but effective implementation requires a nuanced understanding of challenges and opportunities. A comprehensive review of the existing policy and legal framework on bamboo agriculture is needed to identify potential barriers and create an environment for sustainable practices (Ladapo et al. 2017). Understanding the cultural and social context surrounding bamboo in Nigeria and fostering participation to ensure effective community involvement in bamboo-based industries is essential as Nigeria continues to seek to achieve sustainable development goals, constantly constituting local variables and helping to shape the system.

The study of bamboo agriculture covers a variety of disciplines, including agriculture, environmental science, economics, and rural development. Previous studies have emphasized the ecological benefits of bamboo, such as soil conservation, carbon sequestration, and biodiversity enhancement, as well as its various applications from construction to energy (Nath et al. 2015; Li et al. 2015; Song et al. 2011). They also provide insights into their ecological, economic, and social contexts. These studies have precisely established bamboo as a versatile and sustainable resource with numerous benefits. However, there are noticeable differences in Nigeria, a country with a unique agricultural climate and socio-economic development, in terms of specific implications and opportunities. Although some studies have examined bamboo cultivation elsewhere, the differences in context call for a corresponding examination of its role in Nigeria (Lobovikov et al. 2012; Xu et al. 2020).

Regions of Bamboo Cultivation in Nigeria

Bamboo farming in Nigeria is a diverse practice spread across geographical areas, each of which is characterized by specific environmental factors. The southern part of the country, including parts of Cross River, Akwa Ibom, Edo, and Delta states, has sufficient rainfall and a very dry climate, which is comfortable for growing bamboo. Visits to the south western states of Ogun, Ondo, Osun, and Oyo provide new opportunities for bamboo cultivation in the forest. The ecological conditions suitable for bamboo plantations are found in the northern and central regions, especially in the regions of the Nasarawa Plateau, which are transition zones between tropical rain forests and savannas. Even in the north-eastern states like Adamawa and Taraba, characterized by savannah landscapes, bamboo cultivation along riverbanks and areas with sufficient water sources is a potential opportunity. While the northwest, including states like Kebbi, Sokoto, and Zamfara, features semi-arid to arid climates, bamboo cultivation could still be viable with proper water management and the selection of species adapted to drier conditions. Coastal areas, including the Niger Delta and parts of Bayelsa State, present unique conditions for bamboo cultivation, requiring consideration of salt-tolerant species. Furthermore, this practice is not limited to rural areas, as bamboo can be incorporated into parks, greenery, and urban landscaping in urban and peri-urban areas. Generally, bamboo farming in Nigeria demands site-specific assessments, community involvement, and collaboration with local agricultural extension services to adapt to the diverse geographical and environmental contexts across the country.

Theoretical Framework

The theoretical framework guiding this research focuses on several interrelated concepts that combine to inform the methodology and the research. Central to this strategy is the concept of sustainable agroforestry, which means that the integration of trees, crops, and other vegetation can increase agricultural productivity, conserve natural resources, and provide nature that organisms have been able to cope with (Brown et al. 2018; Ogwu et al. 2022).

Within this context, the Triple Bottom Line theory of John Elkington in 1994, emphasizing the interconnectedness of financial prosperity, environmental stewardship, and social equity, serves as a guiding precept for evaluating the multifaceted influences of bamboo cultivation in Nigeria. Additionally, the *Diffusion of Innovations Principle* of Everett Rogers in 1962 presents insights into the adoption and dissemination of sustainable agricultural practices, imparting precious perspectives on overcoming barriers and facilitating exchange within the agricultural quarter.

Objectives of the Study

The aim of the study was to take a critical look at bamboo cultivation in Nigeria, with the aim of addressing current knowledge gaps, providing policy guidance, and specifically promoting the promotion of sustainable agricultural practices. Specifically, It seeks to:

1. Evaluate the effectiveness of bamboo cultivation in soil conservation, carbon sequestration, and biodiversity enhancement within Nigerian ecosystems.

2. Assess the financial feasibility of bamboo cultivation as a means of income generation and value addition across the entire bamboo production chain in Nigeria.

3. Identify the key constraints, potential opportunities, and policy implications associated with the widespread adoption and promotion of bamboo plantations in Nigeria.

4. Expand the understanding of sustainable agroforestry practices, particularly in developing countries, by extracting insights and management recommendations from the Nigerian context.

Apart from these objectives, the study seeks to generate a wider understanding of the role of bamboo agriculture in promoting sustainable agriculture, environmental protection, and rural development in Nigeria.

MATERIALS AND METHODS

An integrated approach was adopted to achieve the objectives of the study, combining ecological analysis, economic analysis, sociological analysis, and policy analysis. Extensive field research was carried out at various sites in Nigeria to address the first objective of assessing the ecological benefits of bamboo cultivation. Soil samples were collected to investigate the impact of bamboo cultivation on soil conservation using standardized methods to assess soil degradation rate and stability. To assess soil erosion rates and stability associated with bamboo cultivation, the study implemented a meticulous procedure employing standardized methods. The following steps outline the methodology:

Sampling Strategy

A combination of purposive and random sampling methods was used to select participants and data sources for the sampling process. Purposive sampling was used to identify key informants with knowledge and experience in bamboo farming to ensure representation of different stakeholder groups, including farmers, policymakers, and researchers. Potential biases were mitigated through rigorous sampling protocols, data triangulation, and validation processes, enhancing the validity and generalizability of the research outcomes.

Site Selection

Various locations representing different agro-ecological zones in Nigeria were selected to study the diversity of soil types and environmental conditions. Bamboo plantations and control sites without bamboo were identified within these locations.

Field Survey and Data Collection

A systematic field survey was conducted at each selected site. Soil erosion factors, such as dams, erosion, and sedimentation, were documented. The analysis included measurement of slope angle and length and identification of soil types.

Soil sampling

Periodic sampling was done to assess various parameters associated with bamboo cultivation. Soil samples were collected from both bamboo and control sites at standardized depths (e.g., 0–10 cm and 10–30 cm). Sampling locations were determined based on a grid design to ensure representative coverage. The pH, organic matter, and nutrient levels of soils were monitored using a standardized test protocol. The height, diameter, and biomass accumulation of bamboos were measured at regular intervals to assess agricultural performance and productivity. These samples were collected using soil augar to prevent cross-contamination between the samples. In addition, environmental variables such as temperature, precipitation, and solar radiation were recorded to understand their effects on bamboo growth and development.

Laboratory analyses

The collected soil samples were sent to the National Root Research Institute (NRRI) at Umudime, in south-eastern Nigeria, for physical and chemical analysis. Basic soil characteristics, including texture, organic matter, and nutrient levels, were determined using standard laboratory methods. These analyses provided insights into the early landscape conditions of bamboo and control sites.

Soil erosion assessment

In order to quantify soil erosion, waterfalls were strategically placed along the vulnerable pathways, taking into account the natural drainage and measuring the accumulated water, and were analyzed to estimate precipitation rates. Additionally, analyses of sedimentation and other leaching factors were used to assess the extent of erosion of stalks and buffer areas.

Stability assessment

The stability of the soil was assessed by methods such as the slake test and aggregate stability analysis. The simplified test involved soaking aggregates of soil in water to assess their resistance to cracking. Aggregate stability analysis examined the ability of soil aggregates to withstand external forces, providing insight into soil structure and susceptibility to degradation.

Data analysis

A statistical analysis was performed on the collected data to compare soil degradation and stability between bamboo and control sites. Analyses included percentages and spatial mapping to identify patterns and correlations.

At the same time, soil samples were prepared to evaluate carbon adsorption capacity. Soil samples were collected from the bamboo plots, measured at different soil depths, and transported to the laboratory for detailed analysis. Standard methods were used to quantify carbon in the soil, providing insight into the carbon storage to which bamboo plantations are susceptible.

To address the development of the ecosystem, the study assessed the variation of plants and animals in the bamboo ecosystem. Field surveys characterized flora and fauna species thriving in and around bamboo plantations. The study highlighted ecological associations of plant species, birds, insects, and other wildlife in bamboo habitats. Particular attention was paid to identifying endemic or endangered species that would benefit from bamboo availability.

The testing of plant and soil ecosystem samples provided a comprehensive understanding of the ecological impacts of bamboo cultivation. This method clarified a strong relationship between bamboo cultivation, carbon sequestration, and biodiversity networks, generating a comprehensive benefit analysis.

Again, an economic evaluation was conducted to determine the viability of bamboo farming in Nigeria. This was achieved through the examination of the entire value chain, from bamboo cultivation to bamboo finished products. Economic parameters such as income and employment generation were quantified through surveys and interviews with bamboo farmers, processors, and entrepreneurs. The value added to bamboo prices was assessed through cost-benefit analysis and market analysis and values were presented in local currency.

Qualitative and quantitative methods were used to assess the social impacts of bamboo farming, while surveys and interviews were conducted in rural areas involved in bamboo cultivation to appreciate its impact on livelihoods and community development. Also, participatory methods, including focus group discussions, were used to explore the cultural significance of bamboo and community engagement in agricultural practices.

In addition, a critical analysis of existing policies on bamboo cultivation in Nigeria through interviews with policymakers, experts, and stakeholders was conducted to identify constraints and policy implications and determine existing barriers and opportunities. Comparative research with successful bamboo farming models in other countries helped formulate policy recommendations to promote their wider adoption.

Finally, to complement existing knowledge, the study gathered empirical insights and practical recommendations from the Nigerian experience and included data from field research, economic analysis, and social analysis combined to provide a comprehensive understanding of the role of bamboo agriculture.

RESULTS

Considering the effects of bamboo root systems and canopy on soil erosion and stability, the findings were interpreted in terms of bamboo cultivation. Studies comparing bamboo and control sites provided insights into the ecological benefits of bamboo cultivation in terms of soil conservation. In addition to these standardized approaches, the study provided a rigorous and scientifically based assessment of the ecological benefits of bamboo farming, particularly in terms of soil erosion rates and complexity in Nigeria. The results are presented in Tables 1–6.

Table 1: Diversity of bamboo cultivation in different ecological zones

Region	**Number of Bamboo Species Cultivated**	**Predominant Soil Type**	**Economic Practices**
North	2	Sandy Loam	Income generation through traditional bamboo crafts, artisanal products.
South-East	3	Clayey Soil	Commercial cultivation for onstruction and furniture industries.
South-West	1	Sandy Soil	Integrated cultivation with crop rotation for local market supply.

Table 1 reflects the diversity in bamboo cultivation practices across different ecological zones in Nigeria. The North, where the sandy loam soil type is prevalent showed limited diversity in bamboo species, focusing on traditional uses and crafts and artisanal products for income generation. The south-east, with predominant clayey soil, showed higher diversity with a focus on commercial cultivation for the construction and furniture industries, while the south-west, made of primarily sandy soil, has moderate diversity and adopts an integrated approach. These variations highlight the adaptability of bamboo cultivation to diverse ecological conditions and economic needs.

Table 2 demonstrates variations in soil characteristics and bamboo growth parameters across different ecological zones in Nigeria. The North, with its semi-arid climate, exhibits slightly alkaline soil pH, moderate soil fertility, and lower bamboo growth compared to the humid tropical conditions of the South-East and the distinct wet and dry seasons in the South-West. Biomass accumulation decreases as the average length and weight of bamboo shoots decrease, while the south-eastern soil is rich in organic matter and nutrients but slightly acidic. Bamboo plants are tall and dense, resulting in high biomass accumulation. The zone is sunny and rainy, reflecting the humid tropical climate. On the other hand, the South-West has slightly acidic soil with moderate organic matter and nutrient levels. Bamboo plants are of intermediate height and diameter, with moderate biomass accumulation. The region experiences high sunlight and moderate rainfall, suggesting a tropical climate with distinct wet and dry seasons. These variations underscore the importance of considering regional factors in bamboo cultivation practices.

Table 3 presents variations in the economic viability of bamboo cultivation across different regions of Nigeria. The South-East posted the highest economic potential, recording higher income generation, more job opportunities, and increased value addition. Bamboo cultivation in the South East generated significant economic returns, averaging N5,400,000 per hectare, creating 2,500 jobs, and increasing the value by N8,400,000 per tonne in terms of distribution. Bamboo growing in the North generated N3,100,000 per hectare, which created 1,500 jobs in the value chain with an added value of N6,000,000, while bamboo growing in the southwest yielded N4,800,000 per hectare, creating 2,000 jobs per ton and an added value of N7,200,000. The economic focus is on balanced income generation, job creation, and value addition. These figures highlight the potential for bamboo cultivation to contribute significantly to economic development.

Table 2: Bamboo cultivation parameters

Region	Soil pH (avg)	Organic Matter (%)	Nutrient Levels	Bamboo Height (cm)	Bamboo Diameter (cm)	Biomass Accumulation (kg)	Environmental Variables
North	6.5	2.0	Moderate	250	3.5	15	High sunlight, Low rainfall
South-East	5.8	3.5	High	300	4.0	20	Moderate sunlight, High rainfall
South-West	6.0	2.8	Moderate	280	3.8	18	High sunlight, Moderate rainfall

Table 3: Estimated economic viability parameters of bamboo cultivation

Region	Income Generation (₦/ha)	Jobs Created	Value Addition (₦/ton)
North	3.1m	1500	6,000,000
South-East	5.4m	2500	8,400,000
South-West	4.8m	2000	7,200,000

Table 4: Ecological benefits of bamboo cultivation

Region	Soil Conservation (Reduction in Erosion)	Carbon Sequestration (tons/ha)	Biodiversity Enhancement (Measured by Species Count)
North	25%	30	10
South-East	40%	45	15
South-West	35%	40	12

Table 4 shows the potential ecological benefits of bamboo cultivation in different parts of Nigeria. The ability of bamboo to prevent soil erosion through its dense roots, combined with effective carbon sequestration and biodiversity enhancement, demonstrated a positive impact on the environment. The observation of increased biodiversity with 15 other species enhanced biodiversity in the south-east. The study recorded significant benefits in soil conservation and carbon sequestration, contributing to environmental resilience. The ecological benefits of a greater percentage reduction of soil erosion and greater carbon sequestration in the Southeast were more pronounced. In the Southwest, bamboo cultivation boosted land degradation reduction by 35% and removed 40 tons of carbon per hectare. The observation of 12 other species increased the diversity of life, soil health, and carbon sequestration in this area. In the north, bamboo cultivation reduced soil erosion by 25%, saved 30 tons of carbon per hectare, and increased biodiversity with the discovery of 10 new species. Thus, the extensive roots of the bamboo mitigated soil erosion and preserved the delicate structure of the soil. These findings highlight the role of bamboo plantations in sustainable land management and contribute to biodiversity conservation and climate change mitigation.

Table 5 shows the ecological characteristics of bamboo plantations, including plant species, bamboo cover, and ecosystems that benefit from bamboo cultivation, indicating the presence of a wide range of species. It also emphasized the ecological importance of bamboo forests in creating protection for endangered species.

Table 6 presents various aspects affecting the widespread adoption of bamboo cultivation, including barriers, opportunities, policy implications, and interpretations. Barriers encompass potential obstacles hindering the broader acceptance of bamboo cultivation. Opportunities, on the other hand, pointed out favorable conditions that can be utilized to promote bamboo cultivation. The regulatory environment was highlighted as a potential obstacle due to the lack of clear regulations, which may impede bamboo cultivation. Clear policies are suggested to encourage farmers and investors, ultimately leading to increased adoption. Limited market access and infrastructure are identified as barriers that can be transformed into opportunities by developing markets and investing in infrastructure.

Table 6: Barriers, opportunities, and policy implications for bamboo cultivation

Category	**Barriers**	**Opportunities**	**Policy Implications**
Regulatory Environment	Lack of clear regulations and guidelines for bamboo cultivation.	Development of clear policies and regulations to support bamboo cultivation.	Formulation and implementation of bamboo-friendly policies and guidelines.
Market Access	Limited market access and inadequate infrastructure for bamboo products.	Development of markets for bamboo-based products; investment in infrastructure.	Government support for market development and infrastructure improvement.
Financial Support	Limited access to financial resources for bamboo farmers and entrepreneurs.	Creation of bamboo-focused funding programs, grants, and financial incentives.	Establishment of financial mechanisms to support bamboo cultivation initiatives.
Technical Knowledge	Insufficient technical knowledge and training for bamboo cultivation practices.	Training programs, workshops, and extension services for bamboo cultivation.	Inclusion of bamboo-specific training in agricultural education and extension.
Land Tenure	Uncertain land tenure and unclear land-use policies for bamboo cultivation.	Establishment of clear land tenure and use policies to encourage bamboo farming.	Integration of bamboo cultivation in national land-use planning and policies.
Research and Development	Limited research and development initiatives specific to bamboo cultivation.	Investment in research to enhance bamboo varieties, cultivation techniques, etc.	Support for research institutions focusing on bamboo-related studies and innovations.
Stakeholder Collaboration	Insufficient collaboration between government, communities, and private sector.	Promotion of multi-stakeholder partnerships and community involvement.	Facilitation of collaborative efforts through forums, workshops, and incentives.

DISCUSSION

The outcomes of the research show the socio-economic impacts of bamboo cultivation in various ecosystems in Nigeria, as well as its environmental significance in the areas of soil conservation, carbon sequestration, and biodiversity improvement. For example, although bamboo cultivation reduced land degradation by 40% in the southeast region, 35% and 25% in the southwest and north, respectively, bamboo farming was found to sequester carbon more, and the southeast showed the highest rate of carbon sequestration at 45 tons per hectare, followed by the southwest and north. This is in agreement with Rathour *et al*. (2022), who reported that bamboo species have multidimensional applications, including bioenergy production, eco-restoration, and economic development, making them a promising crop for sustainable development and environmental management. Furthermore, the study highlights the positive impact of bamboo farming on biodiversity, with increased species diversity found in all areas. The biodiversity associated with bamboo plantations is entrenched in areas of increased availability and resources to feed a variety of plants and animals and contribute to ecosystem health and resilience. Osawaru et al.

(2022) opined that Nigeria's plant diversity and conservation efforts need improvement to ensure sustainable use and conservation of this valuable resource for future generations.

The economic analysis revealed the promising economic potential of bamboo cultivation in Nigeria. Bamboo cultivation generated significant income across the different regions, created employment opportunities, and added value along the production chain. For instance, in the South-East, bamboo cultivation generated an average income of N5.4 million per hectare, creating 2500 jobs and adding value worth N8.4 million per ton. Similarly, in the South-West and North regions, substantial incomes of N4.8 million and N3.1 million per hectare were generated, along with employment prospects and value addition. This reflects the views of Ibrahim and Ogunwusi (2017), who purported that utilizing bamboo as an alternative raw material for textile production in Nigeria could boost capacity utilization, save the country over 500 billion naira annually, and consequently reduce foreign exchange expenditure. These findings underscore the socio-economic significance of bamboo cultivation as a viable sustaining option for rural communities, alleviating poverty and boosting economic development.

The study further revealed the impact of regional variations in soil characteristics, bamboo growth parameters, economic viability, and the importance of considering local ecological conditions and economic contexts in bamboo cultivation practices. For instance, the North region, distinguished by a semi-arid climate and sandy loam soil, showed lower bamboo growth and economic returns compared to the humid tropical conditions of the South-East and the distinct wet and dry seasons in the South-West. These regional variations underlie the need for a guided approach to bamboo cultivation, considering local environmental and economic development. Akamigbo and Nnaji (2011) noted that Nigerian soils were highly vulnerable to climate change impacts and suggested that mitigation and adaptation measures were needed to combat these negative effects on sustainable soil productivity.

Furthermore, the findings of the study showcased important policy implications for promoting bamboo cultivation as a sustainable land management practice in Nigeria. Planners could use the evidence-based strategies provided by the research to design policies and strategies aimed at promoting tree planting, enhancing land conservation efforts, and economic development in rural areas. As such, the implementation of the program includes financial incentives, technical assistance, and capacity building through bamboo farming practices. This is in line with the opinions of Shettima *et al*. (2017) and Gideon (2018), respectively.

In addition, the study also provides valuable insights into bamboo cultivation in Nigeria, focusing on environmental, economic, and social aspects. However, future research endeavors have the possibility for improvement in evaluating sustainable agricultural practices, the value of bamboo products, and the impact of sociocultural practices on local communities. Furthermore, alternative agricultural exploration strategies such as agroforestry and bamboo-based agroecology could be able to enhance agricultural resilience and sustainable development. This insight is in line with Houdanon *et al*. (2018) and Okokpujie *et al.* (2020), who asserted that bamboo use in Nigeria's construction industry reduces environmental pollution, contributes to climate change mitigation, and contributes to economic growth by providing biomass for bio-energy, furniture, and building development.

In summary, the study highlights the various benefits of bamboo farming in Nigeria, including soil conservation, carbon sequestration, economic efficiency, and biodiversity conservation. So policymakers and stakeholders should take holistic approaches, considering environmental, economic, and social aspects when contemplating bamboo cultivation.

CONCLUSION AND RECOMMENDATIONS

The findings on bamboo cultivation in Nigeria underscore the need for key recommendations to ensure sustainability and success in this agricultural practice. Stakeholder collaboration involving government, local communities, and the private sector, is pivotal for shared responsibility and knowledge exchange. Clear policies supporting bamboo cultivation are essential and should be integrated into broader frameworks for agricultural and environmental development. To tap into bamboo's economic potential, investments in market development and infrastructure are paramount, along with financial support mechanisms for farmers. Regular monitoring and assessment are vital for timely interventions and policy adaptation to collectively unlock Nigeria's bamboo resource potential for economic development, environmental sustainability, and social well-being.

To overcome the barrier of limited financial access, the creation of bamboo-focused funding programs and financial incentives is recommended to provide the necessary support. Insufficient technical knowledge was recognized as a barrier that could be addressed through training programs, workshops, and extension services. Recognizing that limited research and development are constraints, additional research is recommended to improve the availability of bamboo varieties, farming techniques, and other resources. Promoting multi-stakeholder partnerships and community participation in bamboo agricultural policies would ameliorate the problem of insufficient collaboration between stakeholders.

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