ISBN: 978-625-90157-4-3

INTEGRATING AI AND MATHEMATICAL MODELS IN AGRICULTURAL SCIENCES

ISPEC

INTEGRATING AI AND MATHEMATICAL MODELS IN AGRICULTURAL SCIENCES- 2026

ISBN: 978-625-90157-4-3

DOI: 10.5281/zenodo.19485513

April / 2026

Ankara / Türkiye

Copyright © 2026 by ISPEC publishing house

All rights reserved. No part of this publication may be reproduced, distributed or transmitted in any form or by any means, including photocopying, recording or other electronic or mechanical methods, without the prior written permission of the publisher, except in the case of brief quotations embodied in critical reviews and certain other noncommercial uses permitted by copyright law. UBAK International Academy of Sciences Association Publishing House®

(The Licence Number of Publicator: 2014/31220)

E mail: info@ispecbooks.com

www.ispecbooks.com

It is responsibility of the author to abide by the publishing ethics rules.

ISPEC Publishing House – 2026©

ISBN: 978-625-90157-4-3

April / 2026

Ankara / Türkiye

INTEGRATING AI AND MATHEMATICAL MODELS IN AGRICULTURAL SCIENCES

AUTHORS

Prof. James O. S BANJO
Assoc. Prof. Neha VERMA
Dr. Oluwole Samuel AJALA
Aisha Simbiat HUSSAINI
Andrea FEHER
Yusuf Usman OLADIMEJI
O.A. ODEBİYİ
J. K. OLADEJO
M.O. ADEYEMİ
E.O. ELİJAH

TABLE OF CONTENTS

PREFACE.....i

CHAPTER 1
INFORMATION COMMUNICATION TECHNOLOGY: PROFICIENCY AND PROFESSIONAL DEVELOPMENT NEEDS FOR AGRICULTURAL EDUCATION PEDAGOGY
Dr. Oluwole Samuel AJALA
Prof. James O. S BANJO 1

CHAPTER 2
AGRICULTURAL DIGITAL SYSTEM, ATTRIBUTES, AND PERFORMANCE: ILLUSTRATIONS FROM NIGERIA Adeoye
Aisha Simbiat HUSSAINI
Andrea FEHER
Yusuf Usman OLADIMEJI1 34

CHAPTER 3
ARTIFICIAL INTELLIGENCE AND SUSTAINABLE AGRICULTURE: ENHANCING PRODUCTIVITY, RESILIENCE, AND FOOD SECURITY
Assoc. Prof. Neha VERMA.....64

CHAPTER 4
SENSITIVITY ANALYSIS OF BOVINE MASTITIS DISEASE: A MATHEMATICAL MODELLING APPROACH
O.A. ODEBİYİ
J. K. OLADEJO
M.O. ADEYEMİ
E.O. ELİJAH 88

PREFACE

Integrating AI and Mathematical Models in Agricultural Sciences brings together a collection of scholarly contributions that explore the transformative role of digital technologies and quantitative methods in modern agriculture. In the face of increasing global challenges such as food security, climate change, and resource constraints, the integration of artificial intelligence and mathematical modelling has become essential for enhancing agricultural productivity and sustainability.

The chapters in this volume address key themes including the role of information and communication technologies in agricultural education, the development and performance of digital agricultural systems, and the application of artificial intelligence in improving resilience and efficiency within farming practices. In addition, the use of mathematical modelling in analyzing agricultural diseases highlights the importance of data-driven approaches in understanding and managing complex biological systems.

By adopting an interdisciplinary perspective, this volume integrates insights from agricultural sciences, data science, and applied mathematics. It contributes to academic discourse while also offering practical implications for researchers, educators, and practitioners working to develop innovative and sustainable agricultural solutions.

It is hoped that this book will serve as a valuable resource for scholars and professionals interested in agricultural innovation, digital transformation, and quantitative analysis, while encouraging further research at the intersection of technology and agriculture.

.

Editorial Team
April 9, 2026
Türkiye

CHAPTER 1
INFORMATION COMMUNICATION TECHNOLOGY: PROFICIENCY AND PROFESSIONAL DEVELOPMENT NEEDS FOR AGRICULTURAL EDUCATION PEDAGOGY

[1] Dr. Oluwole Samuel Ajala
[2] Prof. James O. S Banjo

[1]College of Vocational and Entrepreneurship Education, Department of Agricultural Science Education, Lagos State University of Education, Otto/Ijanikin (Epe Campus), Lagos State, ajalaos@lasued.edu.ng
[2]College of Agriculture and hospitality management, Department of Agricultural Science Education, Tai Solarin University of Education, Ijagun, Ogun State,

INTRODUCTION

The 21st-century educational landscape demands instructional strategies capable of sustaining learner interest and positive attitudes toward productive agriculture. Innovative pedagogy is essential for increasing food production to meet growing global demands. While Information and Communication Technology (ICT) has revolutionized educational processes, many agricultural education lecturers remain products of outdated pedagogical systems. The new teaching techniques and instructional strategies to be employed by educators within the 21st century should be capable of influencing and sustaining the learners' ability, interest and positive attitude in learning productive agriculture. Amedu and Gudi (2017) assert that positive attitudes towards a task foster enjoyment of the task and a drive to seek out opportunities to perform it. The Food and Agricultural Organization (FAO, 2021) found that innovative pedagogy is essential to increasing food production and meeting the demands of the world's growing population. This finding is consistent with the positive attitude of learners fostered by new innovative pedagogy, which will undoubtedly enhance productive agriculture.

United Nations Educational, Scientific and Cultural organization, (UNESCO) (2021) asserts that instructional practices determine how well students learn used by the educators in the classroom. Munyao (2014) also noted that teachers adopt a diverse range of methods and approaches depending on the availability of resources, which may vary across institutions. The modern educator must implement teaching approaches that should thus, be focused on developing in the learners, the acquisition of abilities required for entering into the real world of agricultural production. Therefore, educators of agriculture should ensure that their instructional delivery is carefully crafted to give them the tools they need to succeed in the workforce using appropriate teaching methods (Schneider, 2016). Thus, agriculture education in educational institutions provide learners with the necessary skills to enter the workforce after graduation, either directly or through post-secondary education, teachers must modify their curricula (Schneider, 2016).

Globally, with emergence of COVID-19 outbreak, technology utilization in the field of education is accelerating faster than envisaged and it has become an opening for vast opportunities in human and economic development.

Thus, the incorporation of technology into the existing curricula, can expedite skill acquisition in agriculture, and also bait youths to be more interested in agriculture (Njura, Kubai, Taaliu & Khakame, 2020). Krouska, Troussas, & Virvou, (2019), corroborated that Technological advancements allow the incorporation of multimedia and interactive materials into adult education, which can make learning more engaging and lifelike, motivating adults to develop their skills. Likewise, Studies have demonstrated that when combined into the course work, technology increases activities in the classroom that are focused on the students by using ICT facilities and software like spreadsheets, databases, editing software, word processors, and presentation software are examples of such technologies that help students develop important 21st century abilities including communication, teamwork, and analytical thinking (Barandika, Beitia, Ruiz-de-Larramendi, & Fidalgo, 2015).

This means that the entire agricultural pedagogical process needs to be overhauled using a holistic approach, with the ultimate goal of utilizing ICT to be updated with the rapid advancements in pedagogy across the globe. This no doubt is now an indispensable tool for exploring greater educational opportunities in the 21st century. Elujekwute (2019) argues that ICT has revolutionized educational needs and potential processes, fulfilling educational requirements in new and innovative ways. With the wide range of opportunities and resources available through ICT, students are encouraged to work independently and take ownership of their education. This approach benefits both the lecturers and the students in agricultural education by facilitating quick access to information-based resources.

According to UNESCO (2017), informatics and communication technologies combine to produce the convergence of computer. ICT as defined by Jagadesh (2017) encompasses an extensive array of technological tools and facilities used for information creation, sharing, storing, and administration in addition to communication.

Ajie-Uche, Ajaero, and Efughi (2018) propose that there are four main categories in which ICT utilization can be found: process skill development, concept explanation, idea communication (using PowerPoint, desktop publishing), and knowledge construction and using the web, electronic messaging, databank and web conference to solve problems.

ICT has been acknowledged by Olafare, Adeyanju and Fakorede (2017) as a potent instrument for transforming teaching and learning, allowing students to learn more profoundly and effectively in the classroom. ICT in the current world includes both the equipment that help us manage information and the technology that improve the effectiveness and efficiency of communication. The capacity to utilize ICT as communication, organizing, assessment and information tool for research must be learned. It's also critical to comprehend the ethical and legal ramifications of information use and management. In the twenty-first century, the teaching profession uses more retrieval technologies and networking, communication, and teamwork expertise. Regarding this study, ICT is a tool that may be employed in our postsecondary institutions for instructional delivery, research, and administration—all of which are critical for enhancing pedagogical efficacy.

The productive skills in agriculture can be taught to learners through agricultural education and agricultural science as a subject. Amadi & Lazarus (2017) characterized the teaching of agriculture in higher institutions as agricultural education and it is an important and multifaceted endeavor, encompassing not only the transfer of agricultural knowledge and practices, but also the fostering of responsible and ethical behavior in relation to agriculture. In contrast, Ikehi et al. (2014) state that agricultural science is taught in secondary education with the intention of providing learners with the information and abilities necessary to make prudent use of the scarce resources available to them in order to raise crops and livestock that will feed the world's population and support other agricultural endeavors.

In this context, agricultural education is more precisely defined as a curriculum of instruction and training provided to students in elementary, secondary, and post-secondary educational institutions as well as adult farmers, with the goal of acquiring agricultural production skills to prepare and develop their abilities to establish and produce farm products efficiently for the general

public. In the future, agricultural educators will need to possess pedagogical abilities that include utilizing technology to improve student learning, develop technical proficiency, increase knowledge acquisition, and stimulate the generation of new information (Anderson & Brown, 2019).

For agriculture education lecturers to possess advanced ICT proficiency Learning about agriculture will therefore necessitate the development of an entirely new set of abilities, which will require the construction of creative teaching methods. These include the ability to come up with innovative methods to improve instruction and learning in agriculture education using technology such as applying technology to improve basic and advanced skills, promoting analytical thinking, deepening knowledge, and using the constructivism approach to learn agriculture (Johnson, 2019).

Digital savvy, also known as ICT proficiency, is the ability to use ICT critically and with confidence. It allows people to interact with the public and instill the cultural framework (knowledge, abilities and attitudes) needed to live, work, and learn in a community (UNESCO, 2015). Within the framework of this research, ICT proficiency and improvement alludes to the strategic and practical ability that one possesses to improve one's effectiveness in utilizing ICT for teaching and learning by fostering an environment that is encouraging and dynamic, expanding learning communities, and offering academics tools for instruction and education. According to Dambo & Umah (2018), ICT integration in the educational domain, especially in agriculture education, can enhance teaching methods, expand access to educational opportunities, enhance student outcomes, and streamline educational institutions. Additionally, it can enhance students' performance and achievement, which eventually boosts agricultural educators' pedagogical efficacy.

The foundation of both teaching and learning is pedagogy. Reviewing and updating the pedagogies teachers employ is necessary to educate pupils for the ever-changing challenges of the contemporary world. Therefore Pedagogical improvement is the process of continuously improving teaching strategies and instructional techniques in order to increase student learning results. It entails improving classroom management, curriculum design, assessment methods, and teaching methodologies.

Teachers are always looking for new and creative ways to modify their methods in response to research, student input, and evolving educational environments. Teachers can significantly enhance their pedagogy by reviewing their teaching experiences and remaining up to date on best practices.

In light of the evolving teaching and learning landscape, where traditional classroom dynamics have shifted, it becomes essential for educators to acquire the necessary skills for pedagogical improvement.

Regrettably, academic research highlights a widespread deficiency in educators' capability to use technology in the classroom in an efficient manner (Mormah & Bassey, 2021). Similarly, according to Irele (2021), incorporating technology in teaching presents challenges for educators across all education levels. In this context, Emmanuel (2018) asserts that ICT-proficient lecturers can actively engage with their communities, gaining a deeper understanding of the intricate workings of today's fast-paced, knowledge-driven economy. UNESCO emphasizes that ICT promotes broader educational access, fairness in school, excellent instruction, professional growth for teachers, and effective administration and supervision of education. Consequently, agricultural education instructors must continually enhance their proficiency to leverage ICT tools effectively in administrative tasks, research, and instructional delivery, thereby transforming the current landscape of Nigeria's agricultural sector

The mandate of agricultural education lecturers in tertiary institutions extend beyond instructional delivery. They also engage in research for personal, college, and community development, as well as administrative duties. In their instructional role, lecturers conduct lectures, practical demonstrations on farms or in laboratories, and assess and evaluate learners. In the research capacity, they contribute to national development by investigating contemporary societal issues. Additionally, lecturers handle administrative tasks such as student admissions and registration, student supervision and counseling, and may even hold leadership positions within units, departments, faculties, or entire schools. An ICT-enabled environment can significantly enhance the overall effectiveness of these various areas

According to the aforementioned, in order to effectively teach course material to their students in tertiary institutions in the 21st century, lecturers at these institutions must possess ICT competence. In addition to having a fundamental understanding of technology, educators must successfully integrate it into their lesson plans (Agormedah, Henaku, Ayite, & Ansah, 2020).

This further demonstrates that to improve pedagogical practices as well as other educational practices in their respective institutions, lecturers must be proficient in using ICT to deliver instruction in agriculture education. This is made possible by using ICT tools and resources. ICT competency skills can be defined as clear, quantifiable, standards-based measures of the knowledge and abilities of agricultural education lecturers that have been consistently proven over time in a variety of settings while using different ICT applications for pedagogical efficacy.

ICT integration has enabled a recent and significant shift in the educational landscape from teacher-centric instruction to student-focused learning. If this is a key objective for a particular school system, then a lot of support may be required because this transition is frequently difficult for teachers (UNESCO, 2014). The inevitable replacement of our educational system's foundational traditional pedagogical procedures with ICT-driven curriculum, which produces a domain-specific educational system, is another factor that motivated me to do this study. The results of this study then served as a foundation for thorough data on the proficiency and improvement skills required of agricultural education lecturers in South Western Nigeria's tertiary institutions for improved pedagogy when using ICT.

Statement of the problem

Despite the clear advantages of ICT including speed and flexibility yet agricultural education lecturers in Nigerian higher education have yet to fully tap into its potential. Integration remains challenging due to a lack of proficiency in utilizing ICT for classroom instruction, research, and administrative duties. The Covid-19 outbreak and worldwide technological growths have changed the game in the twenty-first century, and this has further altered how we educate and learn.

Due to the variety of ICT-driven classroom strategies available for lecturers to choose from, teaching approaches and pedagogy have changed. This makes it easier for them to motivate, support, and sustain students' active engagement. It will be up to post-secondary institution agricultural education lecturers to effectively use the wealth of ICT-driven pedagogy for 21st-century agriculture teaching and learning. This will depend on how they can effectively incorporate ICT into instruction delivery in the classroom.

In spite of the indisputable and clear advantages that are derived in the utilization of ICT which include its speed and flexibility in education, agricultural education lecturers in our higher education are yet to fully tap from these potentials. This is discouraging. The reason is not far-fetched because the integration and utilization of ICT is believed to be quite challenging to many agricultural education lecturers who themselves are products of kaput and antediluvian pedagogy (Ajala, 2014) and are yet to fully acquaint themselves with the proficiency in utilizing ICT in the classroom, carrying out research as well as in executing administrative duties. Another significant a roadblock to the effective use of ICT in our classrooms includes incapacity to recognize the proper subset of ICT tools and resources for agricultural education.

If the proficiency abilities needed for utilization of ICT by the agricultural education lecturers in our various tertiary institutions can be identified and included in the programs for skill enhancement and retraining, this should enable the lecturers to be proficient in using ICT for research development, to improve administrative capabilities, and to effectively teach and learn about agriculture in the classroom. Thus, this study determined the ICT resources and equipment required for our classrooms, the level of expertise and development required of agricultural education lecturers in using ICT for research, teaching, and administrative purposes, as well as the obstacles to pedagogical improvement in tertiary institutions in southwestern, Nigeria.

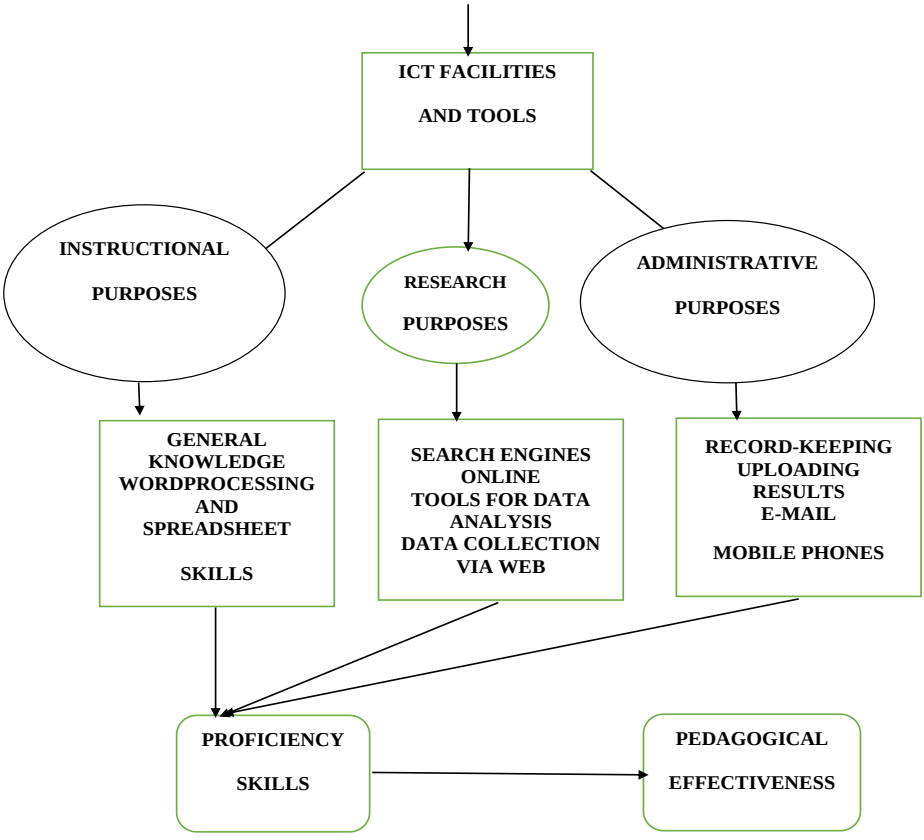
1. CONCEPTUAL AND THEORETICAL FRAMEWORK

Conceptualizing ICT in Agricultural Education

The conceptual framework links ICT (In this context, ICT proficiency refers to the strategic ability to improve teaching and learning by fostering dynamic environments and providing academics with modern tools for

instruction) proficiency (technical, pedagogical, and content knowledge) to pedagogical improvement (effective teaching, student engagement, and learning outcomes).

Conceptual Clarification



.

Figure 1: Conceptual Clarifications

The figure illustrates the various ideas that are covered when using ICT tools and resources by agricultural education lecturers, as well as the proficiency required for research, instructional, and administrative purposes.

These include general knowledge, word processing, spreadsheet skills, and online tools for data analysis and web data collection (Instructional Purposes), record-keeping, uploading results, e-mail, and mobile phones (Administrative Purposes). It also suggests that knowledge of all three subjects can lead to more pedagogically effective agricultural education instruction and learning.

Concept of Agricultural Education

The word "agriculture" was created by combining the Greek terms for land and cultivation, ager and cultural. More than two million years ago, both intentionally and instinctively, agriculture was established. It began with simple tools, which have since been replaced by more sophisticated tools, machinery, and implements. Therefore, agriculture involves the planting of crops and rearing of livestocks purposely for man consumption and supply of raw materials for agro-allied industries. However, agriculture includes more than just the production of food; it also includes the businesses that deal with health, nutrition, and food consumption as well as agriculture-related funding, processing, marketing, and distribution. It also includes the supply and service sectors that support farm production. components of agriculture that also require the application of scientific knowledge includes the exploitation and preservation of land and water resources, the expansion and maintenance of recreational pursuits, and the related political, social, economic, ecological, and aesthetic facets of the nutriment and fiber structure.

Agricultural education and agricultural science are used to teach agriculture. Amadi and Lazarus (2017) define agricultural education as the study of agriculture at postsecondary institutions with the goal of creating people who can successfully live their life and significantly contribute to Nigeria's economy. The goal of agricultural higher education is to prepare students for professions in the industry (Wikipedia, 2016).

Through the acquisition of practical skills in the classroom, practical learning in the laboratory, personal development, and the ability to gather, synthesize, and apply information from a variety of sources to the practical improvement and stewardship of food, fiber, and natural resource systems, agricultural education prepares students for work and/or opportunities for further education in the field.

Within the world economy, it is crucial to use technology for data collection and product production in the food, fiber, and natural resource industries. Hence, using technology can help manufacturers, researchers, producers, and processors compete more successfully in the global market. The use of technology and an appreciation of its possibilities must be ingrained in students as lifelong skills necessary for both career and social survival.

This is easily remedied through the teaching and learning of the integration of scientific and technologically derived knowledge, skills, and attitudes into agricultural output. The phrase "agricultural education" refers to the teaching and training in agriculture provided in post-primary and post-secondary institutions as well as elementary schools. A multitude of comprehensive programs for agricultural vocational education that include both formal and non-formal agriculture education.

Concept of Agricultural education in tertiary institutions

Teaching agricultural education contains using broad body of information on the topic to train learners of agricultural education with sound professional proficiency in the content and practical aspect in order to possess saleable skills to boost agricultural production. Accordingly, the Wikipedia (2020) posited that the majority of agricultural education is taught at higher levels, to prepare students for employment in the agricultural sector. These higher levels are in the various tertiary institutions across the country. The World Bank (2018) defines a tertiary institution as any post-secondary educational setting, including colleges, universities, technical training centers, and vocational schools, both private and public. It is particularly beneficial in fostering growth, reducing poverty, and enhancing overall prosperity.

The goals of agricultural education differ based on the curricula of various postsecondary institutions, such as university faculties of agriculture, colleges of education, and agricultural colleges. The objectives do not really differ from one another as the ultimate goal is to graduate learners in agricultural education with competencies, right skills and attitudes to teach their learners productive skills in agriculture and join the workforce of agricultural production as well. Below, in corresponding order, are the specific goals of the higher levels:

Colleges of Agriculture level

The following objectives are sought to be fulfilled by agricultural education in colleges of agriculture, in the National Board for technical education minimum standards (NBTE, 2012):

i. Produce knowledgeable personnel in adequate number to be e4ffective in technology transfer at farmer's level.
ii. Equip the trainers to function efficiently in the ministries, research institutions and similar organizations.
iii. Provide trainees with sufficient knowledge to comprehend different technologies, enabling them to adopt, utilize, demonstrate, and transfer these technologies effectively.
iv. Get the trainees ready for a career in farming.

Colleges of education level

The following objectives are sought to be achieved by the agricultural education program in accordance with the fundamental standards 2012 benchmarks established by the National Commission for Colleges of Education:

i. Equip teachers with the appropriate attitudes, knowledge, and professional competence in vocational agriculture.

ii. Train teachers who can inspire students to develop an interest in and aptitude for agriculture.

iii. Instill in student-teachers the relevant agricultural knowledge that relates to their specific environment.

iv. Provide student-teachers with the necessary skills and knowledge to effectively establish and manage a model school farm.

v. Offer a solid foundation to support the continued academic and professional growth of student-teachers.

University level

According to the Nigeria University Commission (2012), agricultural science education at the university level is responsible for developing a specialised cadre of agricultural human resources. They create the following specialties through their programs: There are many different types of scientists involved in agriculture, including soil scientists, animal scientists, agronomists, plant breeders, plant pathologists, entomologists, agricultural economists, rural sociologists, veterinarians, forestry specialists, horticulturists, and plant specialists, animal geneticists, agricultural engineers, animal nutritionists, and a host of others.

Curriculum is the most effective method for teaching students about the culture, values, and beliefs of a society, claims Makaran (2015).

The appropriate governing authorities of the colleges of education, colleges of agriculture, and universities establish a minimal standard that includes the curriculum content and resource inputs needed for the program to meet the specified objectives. In order to meet the growing demands of a changing society, a learning institution might use the curriculum as a comprehensive strategy, according to Pillai (2015), to produce a clean, contemporary workforce.

In order to impact particular behavioral changes in learners and assess the extent to which such changes take place, curriculum implementation, according to Fredrick (2015), is the process of planning and carrying out the curriculum's contents. Achieving the learning objectives and facilitating the transfer and retention of knowledge is the primary objective of implementation. Offorma (2014) suggested that the curriculum is accomplished by the suggested interaction between students and instructional resources, methods, and systems for assessing students' achievement of learning goals. A program of studies, an activity program, and a program of recommendations make up the curriculum.

Curriculum as a collection of experiences packaged into an agricultural education program for the goal of educating students in postsecondary institutions in agricultural pedagogy and technical abilities, the National University Commission (NUC), National Commission for Colleges of Education (NCCE), and National Board for Technical Education (NBTE) have granted their approval. There are two main components to the agricultural education curriculum in tertiary institutions: pedagogical content and technical content. The technical content includes crop production, agriculture engineering, agricultural economics, animal production, soil science, and extension. The curriculum for vocational agricultural education must take into account the present difficulties faced by farmers, and it must be creative in order to take into account the production-related practical skills that graduates are expected to have with regard to both crops and animals.

Ogba (2014) states that students in a vocational agricultural program should possess essential scientific knowledge and innovative technical skills for tasks such as operating tractors, planting, harvesting, processing, preserving, storing, and marketing food. Additionally, they should acquire relevant knowledge in aquaculture and livestock.

The education provided in this program must be thorough and well-rounded to support significant agricultural production in Nigeria, as the outcomes are aimed at benefiting both current and future farmers in the community. Therefore, lecturers in agricultural education are very important in creating, implementing, evaluating, and changing the curriculum. An evidence-based curriculum serves as a roadmap for both instructors and students, guiding them toward academic success (Glenn, 2018).

Concepts of Information and Communication Technology In Education

ICTs are cutting-edge, digital tools utilized to process, save, use, document, and retrieve pertinent information that supports educational programs. In this era of information explosion, technology is absolutely necessary because humans retain a significant amount of information externally, beyond the confines of their brain.

Many people in the 21st century now face new options, opportunities as well as difficulties in terms of information storage and retrieval as a result of the widespread integration ICT has permeated nearly every aspect of life, including business, government, education, and public administration. This shift marks a transition into the current era of computer technology within the academic domain are both the results of these global technological breakthroughs in these areas of existence.

Research by Eze, Chinedu-Eze, and Bello (2018) highlights a strong link between the curriculum and ICT, identifying three primary areas where technology can enhance learning. These areas include:

i. The presentation, exhibition, and execution of information using efficient devices;

ii. The use of educational modules—specific applications such as educational games, drills and practice, simulations, instructional tutorials, virtual laboratory observations, representations of complex concepts, musical pieces, and expert systems;

iii. The utilization of information and resources from CD-ROMs, online encyclopedias, interactive maps and atlases, electronic journals, and various references.

The integration of ICT into the curriculum has significantly disrupted traditional pedagogy paradigms. This has resulted to lecturers and trainers encountering challenges that span from developing skills and literacy in ICT usage to providing the essential tools that empower learners to have the capacity to be able to create knowledge and use it appropriately. Although computers were incorporated into the educational system in the late 1970s and early 1980s, no official policy was in place prior to the 1988 release of the National Education Policy for Computers (FRN, 1988).

The 1988 publication provided details on using computers at different tiers of the nation's educational system, as well as information on topics pertaining to fundamental goals, hardware, and software needs. The National policy on Computer education (FRN, 1988) made additional observations regarding teacher preparation, particularly for secondary school levels. 197 teachers from around the nation participated in a training program that served as the catalyst for the policy's adoption.

Additionally, computer systems were incorporated into the secondary schools for the military services as well as the federal unity schools.

The initial enthusiasm eventually faded, and not much progress was made toward the goals that were set. The National Information Technology Policy of 2001, dubbed "Use IT," provided more encouragement for ICT integration in the Nigerian educational system. This marked a significant advancement in the incorporating ICT across the different aspects of the nation's sectors. Two percent of the total national budget and a start-up grant of at least $158 million were two of the recommendations made in the document (FRN, 1988).

Then the Nigerian National Policy on IT (FRN, 2019) was released, and it included an application for all sectors (health, agriculture, and tourism), as well as a vision, mission, general objectives and methods for putting the policy into practice. Ironically, human resource development includes schooling. The plan, among other things, envisioned the creation of IT-specific institutions, facilities, and curriculum for all educational levels in Nigeria. While the said document represents a positive step forward, it fell short of making a meaningful impact on Nigerian education due to its market-driven philosophical framework and insufficient focus on the true infusion and integration of ICT into the country's educational system (FRN, 2019).

The updated National Policy on education (FRN, 2014) further highlighted the necessity of incorporating information technology at every Nigerian school system's level. For example, the paper declared, among other things, that "All states, Teachers Resource Centres, University Institutes of Education, and other professional bodies shall belong to the network of Information and Communication Technology (ICT)" (page 53). In addition, Section 11 Sub-Section 102 of the 32-page paper said that (d) "Government shall provide facilities and necessary infrastructure for the promotion of Information and Communication Technology at all levels of education" (p. 53). The national virtual library effort, which makes use of digital technology to enable simple access to current books, journals, and other information resources, is another important ICT-related element of the strategy (FRN, 2014). This initiative aims to revitalize Nigerian schools.

However, it is imperative to emphasize that there has been very little, if any, effort made to implement the ideas presented in these articles from 2001, 2004, and 2009. Another important policy document pertaining to the use of ICT in education is the Ministerial Initiative on Education for the Nigerian Educational System. This document includes, among other things, the theoretical underpinnings of e-learning in Nigeria, an examination of the nation's setting, e-learning components, the e-education blueprint, strategic features of the blueprint, decade goals (2015), mid-decade goals (2009), and an action plan. The project included policy statements that might hasten the integration of ICT in the educational system, even though it was not broad enough to address ICT integration in Nigerian schools. The education minister who started the paper resigned, though, which probably had an impact on its lack of implementation.

The Federal Unity Schools and Armed Forces Schools trained their teachers, which prepared the way for the 1988 National Policy on Computer Education. The Nigerian Information Technology Development Agency (NITDA) was founded in order to support the effective implementation of the 2001 National Policy on Information Technology (IT). Additionally, the Nigerian National Communication Commission (NCC) founded the Digital Bridge Institute in Abuja to promote ICTs in Nigeria. ICTs haven't had a big impact on Nigeria's educational system, despite these attempts.

Examining the barriers to successful ICT implementation worldwide is relevant given the glaring problems in ICT implementation at various levels of Nigerian education. Doing so could yield insightful insights on how to improve ICT integration in Nigerian schools.

According to Voogt, Fisser, Pareja, Tondeur, and van Braak (2013), factors outside of school-based decision-making drove the adoption of ICT in classrooms and the educational process. Al-Qahtani and Higgins (2012) quotes that “improving the environment for teaching and learning was the primary driver behind the diffusion of technology across many settings, such as universities, schools, and educational institutions”. From the start, the goal of introducing ICT into education was to replace conventional teacher-centered method to teaching and learning with a learner-centered strategy that included the learner coach as an active participant (Voogt et al., 2013).

ICT is defined by UNESCO in 2017 as the mix of informatics technology and several allied technologies, primarily communication technology.Information technology is the term used to describe the hardware, software, and accessories utilized in the gathering, analyzing, managing, and handling of information. Communication is the process of retrieving processed and stored information, distributing it effectively, and then using that information for a variety of purposes in various locations. The emergence of microelectronic and telecommunication tools for the automatic acquisition, analysis, storage, retrieval, manipulation, management, control, movement, display, transmission, reception, and interchange of quantitative and qualitative data is defined as Information and Communication Technologies (ICTs). This definition is supported by Nwabueze and Ukaigwe (2015).

Tertiary institutions' utilisation of ICT in agricultural education provides learners the possibility to put into practice the knowledge gotten from the information they accessed through technologies. According to Volman (2018), efficient use of ICT can transform the way knowledge is taught and acquired, allowing students to interact with it in meaningful, self-directed, and active ways. This will undoubtedly prepare students to become professionals in the field of agriculture after they graduate. Similarly, Bindu (2016) proposed that by giving students the chance to acquire fundamental learning abilities, ICT use can increase students' enthusiasm and involvement.

The use of multimedia computer software to provide audio-visual effects that pique students' attention and involve them in the learning process will allow agricultural lecturers to introduce students to real-world topics that might not be covered in the classroom.

Learning has been enhanced and given greater significance by ICT, allowing students to receive lectures virtually (e-learning) from the comfort of their homes or classrooms. As teachers can continue to instruct pupils even when they are not present, ICT for agriculture education, according to Egunjobi (2015), saves time. Nowadays, technology has overcome geographical restrictions. Virtual classrooms enable a teacher to instruct several pupils remotely. Educators and students can readily connect through phones, Skype, and other devices, enabling creative platforms for teaching and learning to emerge, as demonstrated by the recent COVID-19 pandemic.

Agricultural Education Lecturers' skills Proficiency and Professional development in ICT

A Lecturer is the central figure in the educational process; the lecturer is expected to take actions that will benefit the students (Jimoh, Onah, & Okereke, 2018). According to Mkpanang (2016), the lecturer must foster an environment that encourages meaningful engagement between himself and his learners in the course of instructional delivery in the classroom. In addition to conducting research, a lecturer's responsibilities also include teaching (Pediaa, 2016). Additionally to teaching, some lecturers work in community development. The majority of a lecturer's students are adults, unlike a teacher. As a result, the pupils are better equipped to alter their behavior, accept responsibility, and locate additional resources (Pediaa, 2016).

An agricultural education lecturer is responsible for instructing students and evaluating their understanding of relevant agricultural topics. This individual possesses competence in both the theoretical and practical aspects of agricultural science, focusing on imparting the right productive skills, knowledge and attitudes to students. Hence, pedagogical component involves employing specific techniques and procedures to effectively deliver the content related to agricultural science, ensuring that learning objectives are met.

According to Auwal (2013), agricultural education instructors want to prepare both current and future farmers for success in the agricultural industry. This education was imparted in a practical and useful way that encourages social responsibility, skill development, independence, good work ethics, and spiritual and moral values in those who participate in the educational or learning process. Every lecturer aspires to be an efficient and effective teacher since no one (a lecturer) wants to waste time working toward an unsatisfactory end. Agricultural education lecturers in tertiary institutions not only deliver instructions to learners but also carry out research and administrative duties as part of their job as part of their mandate. The instructional role of the lecturer include lecturing, demonstration of practical on farms/laboratories and through any other means by teaching, assessing and evaluating the learners. The lecturer contributes to national development while also developing him professionally through conducting researches on contemporary issues in the society.

The lecturers are also involved in carrying out some administrative roles which may include learners' admission and registration process, supervising and counselling the students, and appointment to head or direct a unit, department, and faculty, manage an institute or the entire school.

Education, like every other sphere of human endeavours, has experienced tremendous progress over time especially in the twenty-first century occasioned mainly by the Covid-19 outbreak. The definition of an effective and efficient teacher in this 21st century is no longer the same as the definition in the 19th or 20th centuries. Pedagogical practices that used to undermine the teaching profession in times past have given way to new norms. A 19th or 20th century teacher did not need to teach with a computer nor need to use a projector or PowerPoint, Zoom, Thaquiz, Google Classroom or Microsoft in the delivery of instructions to the learners. He or she did not need to hold a virtual classroom nor need to own a laptop, a printer or a scanner. Teaching in his or her time did not require technological skills; what was required during his or her time was good mastery of one subject or a collection of subjects. In the 21st century, reverse is the case as all these are needed by the teacher to be able effective in his pedagogical practices.

ICT can transform pedagogy and give students greater agency in the classroom and throughout the school.

Teachers in this environment must be able to incorporate ICT into their pedagogical practices to maintain parity and high standards in the learning process. The development of knowledge and social skills in students, such as teamwork, critical and creative thinking, complex problem solving, and socio-emotional talents, ICT proficiency is also required of teachers. Therefore, in achieving the benefits of investments in ICTs, it is essential to prioritize teacher in-service training and continuous, relevant professional development for educators. To make certain that educators are able to ensure their pupils are developing the necessary abilities, including digital competences, they must receive training and on-going technical assistance.

In order to guide in-service and pre-service teacher professional development in using ICT in all the educational system, UNESCO (2018) developed the Information and Communication Technology Competency Framework for Teachers (ICT-CFT).

The ICT-CFT is a dynamic framework that may be tailored to meet institutional and national objectives while providing a framework presently for policy creation and enhancing capacity in education. The 18 competencies that make up the ICT-CFT are categorized into three levels of ICT pedagogical usage by teachers and are based on the six elements of their professional activity. The fundamental idea is that teachers who are adept at utilizing ICT in the classroom would be able to successfully guide students' ICT skill development while still delivering high-quality instruction.

According to UNESCO (2018), the following six aspects of a teacher's professional activities are addressed:

i. Understanding ICT in Education Policy

ii. Curriculum and Assessment

iii. Pedagogy

iv. Application of Digital Skills

v. Organization and Administration

vi. Teacher Professional Learning.One persuasive finding from the studies is that, when done well, integrating technology into education has a significant, beneficial influence on student achievement (Olelewe & Agomuo, 2016). Ogbuanya & Bakare (2017) assert that although integrating technology into the classroom improves instruction, it cannot replace a teacher in underdeveloped countries like Nigeria

According to the previously mentioned objectives, agricultural education is practically oriented and involves the development of cognitive and psychomotor skills, hence the instructional content is better delivered through a learner-centred approach with the learner exposed to myriads of experiences which helps them to have adequate theoretical and practical knowledge which will then enable them to demonstrate competencies in the psychomotor skills needed in Agricultural production.

ICT-driven instructional materials if carefully prepared and utilized aid the lecturers in broadening the horizons of his students' experiences. The following headings are used to organize these educational materials:

i. **Visual Materials**- These consist of visual aids like pictures, diagrams, flannel boards, chalkboards, buildings, graphs, and charts that the instructor has prepared.

ii. **Audio Materials**- This includes items such as language labs, discs, radios, tape recorders, cassette cartridges, and teachers' voices, and so on that appeal to the sense of hearing.

iii. **Audiovisual Materials**- These materials make use of both the hearing and vision. They create or make use of both images and sounds, such as slides and film strip projections with audio, televisions, and motion pictures.

iv. **Software:** This category includes cassettes, written materials, filmstrips, graphic materials, and overhead transparencies. A slide projector is used to present most of the content.

v. **Hardware-** These are the tools that are utilized to deliver content. For instance, projectors, video recorders, tape recorders, and chalkboards. Video recorders are the equipment, whereas videotape is the medium.

vi. **Projected Materials**- This also applies to materials that need to be viewed through projections. Transparent and transparent (opaque) projections are the two varieties. Books, visual aids, games and simulations, books, chalkboards, bulletin boards, charts, graphical graph diagrams, etc. are a few examples of non-projected resources.. The technical ability of the Agricultural Education teachers to determine the appropriateness, suitability, durability, attractiveness and simplicity is a precondition for effective use of ICT pedagogical innovation in agricultural education teaching and learning

2. CHALLENGES TO ICT ADOPTION

ICT is a powerful tool for transforming teaching, enabling students to learn more effectively. However, Nigerian tertiary institutions face significant challenges, including inadequate infrastructure, lack of technical knowledge, and poor funding. Literature distinguishes between general ICT literacy and the specific pedagogical integration required to shift from teacher-centric to student-focused learning. In the future, educators must possess skills that stimulate the generation of new information rather than just retrieving existing data. Research by Ajala (2024) underscores a critical demand for digital infrastructure within agricultural education, noting that 90% of identified ICT tools most notably interactive whiteboards, printers, and video players (94.2%

each) are essential for effective pedagogy. However, the study reveals a stark "proficiency gap" across all professional domains. Of the 93 instructional skills assessed, 89 yielded a positive Improvement Need Index (INI), highlighting urgent deficiencies in multimedia delivery and Learning Management System (LMS) integration.

The need for professional development extends into research and administration, where training is critically required for anti-plagiarism software, digital data collection, and cloud-based record management. Furthermore, Ajala (2024) Kruskal-Wallis H test results indicated significant perceptual differences between lecturers and technologists, suggesting that professional development initiatives must be tailored to the unique technical and pedagogical requirements of each group.

Most of the sectors of the economy have continually utilized ICT in their daily activities while the educational sector continues to lag behind in its utilization. It is disheartening in this contemporary digital era that many employees at Nigerian academic institutions lack ICT computer literacy, according to Idowu, Esere, and Iruloh (2017). Even so, as stated by Jumare, Tahir, & Hamid (2017) and Amusa & Atinmo (2016), this varies between institutions and amongst employees within the same institutions.

This is also supported by Oladimeji & Folayan (2018), who note that although there has been a great deal of technological advancement since ICT was first incorporated into the Nigerian educational system in the 21st century, there are unquestionably a lot of challenges and barriers that have emerged that make it difficult to use ICT for pedagogy. various challenges are believed to be various impediments and challenges.

The lack of computer literacy and skills (Olelewe & Okwor, 2017), the epileptic power supply in Nigerian tertiary institutions (which is seen as a major barrier to ICT adoption), and really all industries (since they all depend on electricity to run ICT and electronic devices) are the main obstacles in effective incorporation of ICT in teaching and learning process, according to some studies (Azuh & Modebelu, 2014). A lack of institutional support was highlighted by Enakrire & Ocholla (2017) and Al-Dheleai, Baki, Tasir, & Al-Rahmi (2019), among others. This deficiency in support can hinder the effective implementation of educational initiatives and limit opportunities for

professional development, ultimately impacting the overall quality of education.

Barriers hindering the effective utilization of ICTs in higher institutions include lack of funds for procurement of computers, poor network, insufficient educators' education and retraining in the latest technologies, lack of maintenance skills, lack of maintenance of the existing technologies and upgrading, lack of requisite facilities, lack of government support and business (Eleanor, 2017). George (2016) envisaged that lack of all stakeholders' awareness of the benefits of ICT for education is a challenge. These stakeholders include teachers, parents, students and the community at large.

George (2016) also mentioned that some of the obstacles to using ICTs in school include a absence of ICT in classrooms, a dearth of opportunities for lecturers to grow professionally in the classroom, and a shortage of time to incorporate ICTs into the current curriculum. He also recommended that local software developers collaborate with institutions to create training-specific software. According to Okereke (2017), the majority of Nigerian institutions have low ICT awareness since they don't have enough staff members, resources for technological learning, knowledge, or computer-assisted instruction.

CONCLUSION

There is a consensus that both lecturers and technologists require significant skill upgrades to remain relevant in a 21st-century technological landscape. Proficiency is not just about tool usage but about the effective pedagogical application of these tools. The way we teach agriculture has a cumulative effect on the production of what we eat and this has created a gap between the quantity of food needed and quantity supplied. Therefore the agricultural sector needs to be over-hauled in a holistic approaching order to meet the recent global technological advancement in pedagogy utilizing information and communication technologies. Hence, it is expected that Agricultural education lecturers' upgrade and update their ICT skills.

The majority of lecturers in agricultural education lack the expertise in using ICT for teaching and learning that is required, mostly because they are products of antediluvian pedagogy and kaput.

Aside from that, they confront a plethora of difficulties brought on by inadequate finance, a bad power supply, expensive ICT infrastructures, and internet access, among other issues. In the face of social, scientific, and pedagogical challenges, lecturers might use ICT to increase the efficacy and efficiency of educational activities. Consequently, to guarantee the successful integration of ICT in the efficient teaching and learning of agricultural education, an interdisciplinary and integrated strategy is needed.

Thus, in addition to conducting a need assessment analysis on the proficiency skills required by lecturers in agricultural education for instructional, research, and administrative use of information and communication technology for pedagogical improvement in tertiary institutions in South-West Nigeria, this study work identified ICT facilities and tools that are necessary for effective utilisation of ICT. The findings demonstrated that most of these proficiency abilities in using ICT for teaching and learning cannot be performed by lecturers in agriculture education; therefore, in order to be pedagogically effective, they must acquire the proficiency and improvement skills highlighted in this study.

Recommendations

In light of the identified proficiency gaps, the following measures are recommended for implementation:

i. University and college governing bodies ought to set up specialized training and retraining initiatives., intensive seminars, workshops, conferences for the agricultural education lecturers to enlighten and equip them with proficiency skills in the utilisation of ICT to keep their knowledge current and improved for effective delivering of instructions to their learners, successfully completing research tasks with minimal error and effectively carrying out specified administrative responsibilities.
ii. To encourage collaborations between nonprofit organizations and philanthropic individuals in the advancement of information and communication technology, government officials at all levels and school administrators alike should provide sufficient institutional and technical support, as well as purchase and upkeep of the necessary ICT equipment

and facilities for postsecondary educational institutions. This will facilitate the use of ICT.

iii. The different administrators of tertiary institutions should proffer lasting solutions to the constraints of utilization of ICT most especially erratic power supply which is as a major constraint to the utilization of ICT in most of the higher education institutions. This will be beneficial to encourage the usage of ICT facilities and tools for instructional, research and administrative purposes in the tertiary institutions.

iv. There should be a review of the Agricultural education curriculum in tertiary institutions that will inculcate the utilization of ICT for effective pedagogy should be considered in the review.

v. The government should allocate sufficient funds for the inclusion of ICT to school administrators across all school levels beginning from the primary education through the tertiary institutions.

REFERENCES

Agormedah, E. K., Henaku, E. A., Ayite, D. M. K., & Ansah, E. A. (2020). Online learning in higher education during COVID-19 pandemic: A case of Ghana. *Journal of Educational Technology & Online Learning, 3*(3), 183–210.

Ajala, O. S. (2014). *Assessment of Agricultural education lecturers' e-learning skills in the effective teaching and learning of agricultural education in tertiary institutions in Ojo Local government area of Lagos State* [Unpublished master's dissertation]. University of Nigeria, Nsukka.

Ajala, O. S. (2024). *Information communication technology proficiency and improvement need of agricultural education lecturers and technologists for pedagogical improvement in tertiary institutions in Southwest Nigeria* [Doctoral thesis]. Tai Solarin University of Education, Nigeria.

Ajie-Uche, G., Ajaero, O., & Efughi, A. (2018). Capacity building needs of Business Education Lecturers in ICT-based teaching in tertiary institutions in South-South Nigeria. *Nigerian Journal of Business Education (NIGJBED), 5*(1), 323–335.

Al-Dheleai, Y. M., Baki, R., Tasir, Z., & Al-Rahmi, W. M. (2019). What hinders the use of ICT among academic staff at Yemen's public universities? *International Journal of Humanities and Innovation (IJHI), 2*(1), 13–24.

Al-Qahtani, A. A. Y., & Higgins, S. E. (2013). Effects of traditional, blended and e-learning on students' achievement in higher education. *Journal of Computer Assisted Learning, 29*, 220–234.

Amadi, N. S., & Lazarus, S. T. (2017). Current issues in agricultural education in tertiary institutions in Nigeria. *International Journal of Agriculture and Earth Science, 3*(1), 13– 18.

Amusa, O. I., & Atinmo, M. (2016). Availability, level of use and constraints to use of electronic resources by law lecturers in public universities in Nigeria. *JLIS.it, 7*(3), 139–172.

Anderson, J., & Brown, S. (2019). Innovative approaches to integrating technology in agricultural education. *Journal of Agricultural Education and Extension, 25*(4), 295–311.

Auwal, A. (2013). Effects of teaching method on retention of Agricultural Science knowledge in senior secondary schools of Bauchi Local Government Area, Nigeria. *International Journal of Science and Technology Educational Research, 4*(4), 63–68.

Azuh, O. J., & Modebelu, M. N. (2014). Academic staff challenges to effective utilization of information and communication technology (ICT) in teaching/learning of agricultural education. *International Letters of Social and Humanistic Sciences (ILSHS), 2*, 88–96.

Barandika, G., Beitia, J. I., Ruiz-de-Larramendi, I., & Fidalgo, M.-L. (2015). Innovation management (Une-Cen/Ts 16555-1:2013) applied to superior education: Integration of disruptive technologies for the teaching of chemistry. *Proceedings of the Edulearn15: 7th International Conference on Education and New Learning Technologies*, 2255–2260.

Bindu, C. N. (2016). Impact of ICT on teaching and learning: A literature review. *International Journal of Management and Commerce Innovation, 4*, 21–31.

Dambo, B. I., & Umah, M. H. (2018). Accessibility and utilization of information and communication technology facilities for learning business studies in public junior secondary schools Port Harcourt metropolis. *International Journal of Innovative Social & Science Education Research, 6*(4), 83–90.

Egunjobi, A. (2015). Teachers' and learners' ICT-readiness assessment for agricultural science instruction in Oyo State, Nigeria. *Research on Humanities and Social Sciences, 5*(14), 121– 129.

Eleanor, A. A. (2017). *Challenges in utilization of technologies in universities* [Unpublished lecture notes].

Elujekwute, E. C. (2019). *Influence of tertiary education trust fund (TETfund) on provision of Information Communication Technology (ICT) facilities in public universities in South- East states of Nigeria*

[Unpublished doctoral thesis]. Benue State University, Makurdi, Nigeria.

Emmanuel, N. (2018). *Information and communication technology in education in Nigeria*. https//:www.google.scholar.com

Enakrire, R. T., & Ocholla, D. N. (2017). Information and communication technologies for knowledge management in academic libraries in Nigeria and South Africa. *SA Journal of Information Management, 19*(1), 1–9.

Eze, S. C., Chinedu-Eze, V. C., & Bello, A. O. (2018). The utilisation of e-learning facilities in the educational delivery system of Nigeria: A study of M-University. *International Journal of Educational Technology in Higher Education, 15*(34), 1–20.

Federal Republic of Nigeria. (1988). *National policy on information technologies (ICT) in education* (Note: Snippet shows 2019 reference; please verify if 1988 is the intended date).

Federal Republic of Nigeria. (2014). *National policy on education* (Revised ed.). NERDC Press.

Federal Republic of Nigeria. (2019). *National policy on information technologies (ICT) in education*. https://education.gov.ng/wp-content/uploads/2019/08/NATIONAL-POLICY- ON-ICT-IN-EDUCATION-2019.pdf

Food and Agriculture Organization. (2021). *Regional overview of food security and nutrition in Africa 2021*. https://doi.org/10.4060/cb1667en

Fredrick, F. T. (2015). *Prospects and challenges of e-learning in Nigerian university education using National Open University of Nigeria Akure Study Centre* [Unpublished bachelor's dissertation]. Adekunle Ajasin University, Akungba Akoko.

George, C. (2016). *Importance, benefits and advantages of ICT in schools today*. https://www.myorticlelibrary.com

Glenn, S. (2018). *Importance of curriculum to teaching*. Classroom. https://classroom.synonym.com/importancecurriculum-teaching-6189570.html

Idowu, A., Esere, M., & Iruloh, B. R. (2017). Computer accessibility, usage and lecturers' perception of innovative ICT based assessment in a

Nigerian university. In *Sustainable Transformation in African Higher Education* (pp. 215–226). Springer.

Ikehi, M. E., Ifeanyieze, F. O., & Ugwuoke, C. U. (2014). Integration of climate change into the senior secondary school agricultural science curriculum in Nigeria. *Journal of Atmospheric and Climate Sciences, 4*, 614–621.

Irele, A. O. (2021). Digital integration into the Nigerian educational system: Challenges and prospects. *Texila International Journal of Academic Research, 2021*, 17–23.[1]

Jagadesh, M. (2017). ICT tools usage among faculty of educat[2]ion in teaching learning. *International Journal of Indian Psychology, 4*(2), 72–76.

Jimoh, B., Onah, B. I., & Okereke, G. K. O. (2018). Capacity building needs of lecturers in e- teaching for effective delivery of computer and electrical/electronic technology courses in tertiary institutions in Southwestern, Nigeria. *International Journal of Applied Engineering Research, 13*(11), 8736–8750.

Johnson, M. (2019). Using technology to deepen knowledge and encourage analytical thinking in agricultural education. *Agricultural Education and Communication, 102*(3), 25–30.

Jumare, M. A., Tahir, S. M., & Hamid, A. T. (2017). The use of ICT in Nigerian universities: Study of Kaduna State University, Kaduna. *International Journal of Advanced Research in IT and Engineering, 6*(7), 1–12.

Krouska, C., Troussas, C., & Virvou, M. (2019). A literature review of social networking-based learning systems using a novel ISO-based framework. *Intelligent Decision Technologies, 13*(1), 23–39.[3]

Makaran, D. (2015). *Factors influencing curriculum development process in secondary school education in Mogadishu, Somalia* [Master's thesis, University of Na[4]irobi]. http://erepository.uonbi.ac.ke/bitstream/handle/11295/97403/

Mkpanang, J. (2016). Effects of class-wide and reciprocal peer tutoring strategies on students' mathematical problem-solving achievement in electricity concepts in physics. *International Journal of Education, Learning and Development, 4*(3), 37–44.

Mormah, F. O., & Bassey, B. A. (2021). Teacher education in Nigeria and the emerging technologies in the 21st century classroom. *African Educational Research Journal, 9*(3), 641–647.

Munyao, P. (2014). *Impact of in-service training on the performance of chemistry in the Kenya Certificate of Secondary Education (KCSE) in secondary schools in Kangundo Sub-County Machakos County* [Master's thesis, University of Nairobi].

National Board for Technical Education. (2012). *Report of the National Steering Committee on the development of National Vocational Qualification Framework (NVQF) for Nigeria: Focus on primary education*. University of Calabar Press Ltd.

National Universities Commission. (2012). *Manual of accreditation procedures for academic programmes in Nigerian universities*. www.dspace.funai.edu.ng

Njura, H. J., Kubai, K. I., Taaliu, S. T., & Khakame, S. K. (2020). The relationship between agricultural teachings approaches and food security in Kenya. *Education Research International, 2020*, 1–12. https://doi.org/10.1155/2020/8816400

Nwabueze, A. I., & Ukaigwe, P. C. (2015). Application and utilization of information and communication technology devices for record management in universities in South-East, Nigeria. *Journal of Education in Developing Areas (JEDA), 23*(2), 323–335.

Offorma, G. (2014). *Approaches to curriculum development* (pp. 77–92). https://www.researchgate.net/publication/280554159

Ogba, E. I. (2014). Challenges and prospects of technical and vocational education and training for youth empowerment in vocational agricultural education. *Journal of Society for Science and Nature, 5*(3), 169–172.

Ogbuanya, T. C., & Bakare, J. (2017). Development of appropriate e-teaching contents for capacity building of technical education lecturers of colleges of education in Lagos State. *IJUNSST, 10*(8).

Okereke, O. (2017). Causes of failure and abandonment of projects and project deliverables in Africa. *PM World Journal, 6*(1), 1–16.

Oladimeji, T. T., & Folayan, G. B. (2018). ICT and its impact on national development in Nigeria: An overview. *Research & Reviews: Journal of Engineering and Technology, 7*(1), 7–11.

Olafare, O. E., Adeyanju, S. E., & Fakorede, O. R. (2017). Integrating ICT into teaching and learning: Opportunities and challenges for education. *Eurasia Journal of Mathematics, Science and Technology Education, 13*(7), 3553–3567. https://doi.org/10.12973/eurasia.2017.00739a

Olelewe, C. J., & Agomuo, E. E. (2016). Effects of B-learning and F2F learning environments on students' achievement in QBASIC programming. *Computers and Education, 10*(3), 76– 86.

Olelewe, C. J., & Okwor, A. N. (2017). Lecturers' perception of interactive white-board for instructional delivery in tertiary institutions in Enugu State, Nigeria. *Journal of Computers in Education, 4*(2), 171–196.

Pediaa. (2016). *Difference between teacher and lecturer*. http://pediaa.com/difference-between- teacher-and-lecturer

Pillai, S. (2015). *Curriculum design and development*. https://docplayer.net/5749858-Curriculum- design-and-by-prof-sswaminatha-pillai.html

Schneider, G. (2016). Cultivating careers through work-based learning. *The Agricultural Education Magazine, 89*(3), 13–15.

UNESCO. (2014). *Education for All 2013-2014: Teaching and learning: Achieving quality for all*. UNESCO.

UNESCO. (2015). *Current issues and trends in technical and vocational education*. UNESCO.

UNESCO. (2017). *ICT in education*. United Nations Educational, Scientific and Cultural Organization.

UNESCO. (2018). *ICT competency framework for teachers*. UNESCO.

United Nations Educational, Scientific and Cultural Organization (UNESCO). (2021). *Effective and appropriate pedagogy*. https://learningportal.iiep.unesco.org/en/issue-briefs/improve-learning/teachers-and-pedagogy/

Volman, M. C. (2018). Evaluation of information and communication technology in teaching and learning of economics in secondary schools. *Journal of Educational Research, 13*(6), 177– 188.

Voogt, J., Fisser, P., Pareja Roblin, N., Tondeur, J., & van Braak, J. (2013). Technological pedagogical content knowledge – a review of the literature. *Journal of Computer Assisted Learning, 29*, 109–121.

Wikipedia. (2016). *Information and communication technology* (Note: Snippet shows 2020 version; verify if 2016 is required).

Wikipedia. (2020). *Agricultural education*. In Wikipedia, The Free Encyclopedia. https://en.wikipedia.org/wiki/Agricultural_education

World Bank. (2018). *Definition of tertiary institution*. http://www.worldbank.org/en/topic/tertiaryeducation

CHAPTER 2
AGRICULTURAL DIGITAL SYSTEM, ATTRIBUTES, AND PERFORMANCE: ILLUSTRATIONS FROM NIGERIA

[1] Aisha Simbiat HUSSAINI
[2]Andrea FEHER
[3]Yusuf Usman OLADIMEJI1

[1]Ahmadu BelloUniversity, Zaria, Department of Agricultural Economics ashussaini@abu.edu.ng, ORCID ID: 0000-0002-1212-142X
[2]University of Life Sciences "King Mihai I" from Timișoara, Faculty of Management and Rural Tourism, Department of Economy and Firm Financing,
[3]Ahmadu BelloUniversity, Zaria, Department of Agricultural Economics

INTRODUCTION

Overview of Nigerian Agricultural Technological System / Evolution

Agriculture remains foundation of the Nigerian economy despite the country's heavy dependence on oil for several years. Nigeria with a 923,000-hectare arable land and 57,300 km^2 suitable for irrigation and a considerable proportion of her over 200 million population directly engage in agriculture (Abubakar et al., 2024). The country should be self-sufficient in food production but for the small-scale farmers reliance significantly on crude technology and generally (Attah, 2012), the peasant nature of the agricultural sector, the nation's agricultural potentials are far from being fully realized and this has unpalatable implications for food security and sustainable economic development of the country (Isah, 2022; Abubakar et al., 2024).

The agricultural sector in Nigeria is dominated by small farm holders who are associated with generally with low technologies' adoption and very low adoption of agricultural digital systems, resulting in low productivity, output, income, savings and investment (Sennuga et al., 2020). Like in other parts of developing nations, the productivity of most of the farm commodities is comparatively lower than the potential yield in Nigeria and actual yield in agriculturally progressive nations (Isah, 2022). For example, the productivity of the maize production in Nigeria is comparatively lower, average 1.8 tons per ha than the potential yield in Nigeria, average 5 tons per ha and actual yield in agriculturally progressive nations, average 8 tons per ha (PwC 2021). However, all indicators of welfare in Nigeria are worsen such as food insecurity, poverty, malnutrition and hunger reduction crucially depend on increased productivity and profitability of diverse small-scale farmers who constitute more than 75% of farming populace (Nnamonu et al., 2021). It is for these reasons that any attempt at modernizing agriculture should aim at transforming small-scale farming.

One of the ways to transform agriculture in Nigeria is by introducing small-scale farmers to agricultural digital tools and other modern agricultural practices (Isah, 2022). Technological change has been a significant factor driving modernization and improvement in agriculture in the recent past.

For example, a comparison of Nigeria's rice yield per hectare is significantly lower than that of the United State. Nigeria's average yield is around 2.01 metric tons per hectare. The average rice yield in the United States is around 7,616 kg per hectare (IITA, 2017; USDA, 2018). This is significantly higher than Nigeria's yield. The main explanation for such increase is changes in agricultural production methods, topmost among which is the use of innovative improved technologies such as digital tools.

Methodology

Following the backdrop, this chapter traces the historical development of agriculture digital systems, attributes, performance and illustrations from Nigeria including the extent of precision agriculture adopted in Nigeria agricultural sector, future perspectives of the sector digital revolutionary system in Nigeria were presented. In this chapter, the authors reviewed empirical and review materials from reliable databases such as web of science, google scholar research gate. Secondary data were also reviewed from world bank statistics data Through the collection and analysis of empirical literature and non-numerical data, this paper employed qualitative research methodology to contextualize opinions, comprehend the experience, and juxtapose concepts. This process aids a researcher in gaining deep insights into a problem in order to generate new ideas. Thus, pertinent research journals, papers, publications, comments, and editorials were critically examined in the study.

Evolution of Primitive Agriculture to Agricultural Digitilization

Technological advancement is an innovative tool that defines economic growth and development across the globe, including Nigeria . Agriculture evolved progressively over time, from crude to advanced. Agriculture's technological improvements are separated into four long-term phases, known as the transformation from Agriculture 1.0 to Agriculture 4.0. Agriculture 1.0 refers to the period of typical agricultural practices from the antique eras, when humans are hunter-gatherer lifestyles and fruits collector and transit to primarily utilized domestic hand tools for cultivation, relying on manpower and animal forces, to the end of the nineteenth century.

Agriculture 2.0 is defined as the time from 1784 to nearly 1870 when agricultural machinery was used for soil tillage, sowing, weeding, irrigation, and harvesting (Liu et al. 2021), resulting in increased food production and fewer hand employment (1784-1870). Soil tillage, planting, weeding, irrigation, and harvesting were all done with machines (Liu et al., 2021). Thanks to developments in electronics and computing, Agriculture 3.0—also known as "precision farming"—was born. By improving the operational performance of agricultural systems, these advancements reduced the need for pesticides in the field, saved energy when using machinery, and saved water for irrigation (Ahmad & Nabi 2021). The third key feature of agriculture in its historical development, often referred to as "Agriculture 3.0" or "Technological Agriculture", is characterized by the integration of scientific advancements and technological innovations leveraging on knowledge from fields like botany, plant physiology, engineering and chemistry to optimize crop yields, nutrient management, and pest control so as to enhance productivity and efficiency. This stage involves the application of scientific principles to develop new tools, techniques, and practices. This era sees the development and application of machinery, tools, and techniques that reduce labor intensity and increase productivity.

As to the International Society of Precision Agriculture's. (PA) definition to improve resource efficiency, productivity, quality, profitability, and sustainability of agricultural production, "precision agriculture is a management strategy that collects, processes, and analyzes temporal, spatial, and individual data and combines it with other information to guide site, plant, or animal specific management decisions." (ISPA 2021).

It is pertinent to note that Agriculture 4.0, a modern phase in agricultural development, is characterized by the integration of advanced technologies like IoT, AI, Automation and Robotics and big data to enhance efficiency, sustainability, and precision in farming practices (David et al., 2022). It builds upon the historical advancements in agriculture, including the Neolithic revolution, the industrial revolution, and the green revolution, each marked by significant technological leaps and societal changes (David et al., 2022).

Agriculture 4.0 leverages digital technologies to optimize various aspects of agriculture, including precision farming, crop monitoring, automated harvesting, and supply chain management. In essence, Agriculture 4.0 represents a convergence of technological advancements and sustainable practices to address the challenges of feeding a growing global population while minimizing environmental impact, building upon the foundation of historical agricultural developments.

The efficacy of the agricultural sector depends on a digital drive for real-time agricultural information The term "Agricultural Digital System" describes how digital technologies are being used in agriculture to increase sustainability and production. Biological actors, automation and robots, digitalization and big data, and vision and sensors are examples of key technologies. For these technologies to function well together, connectivity is essential (Ufuk & Mehmet, 2021).

Digital Technology

Digital technologies have proved useful in various sectors such as health, manufacturing, finance, and agriculture (Mohapatra *et al.*,2022).

Digital technologies increase productivity, enhance quality, and promote environmental sustainability in the agricultural sector (Saiz-Rubio and Rovira-Más, 2020). Digital transformations through "Industry 5.0" are transforming agriculture through precise and real-time decision-making in farming activities (Saiz-Rubio and Rovira-Más, 2020). Internet applications and mobile phones, among other digital technologies, are changing how people communicate and its prospects in agriculture have advanced significantly (FAO and ITU, 2017). According to Sturgeon *et al.* (2017), there is a chance that the "New Digital Economy" may lead to the creation of digital solutions for numerous problems facing agricultural development. The integration of digital technologies in agriculture not only enhances efficiency within agricultural value chains but also supports the three pillars of Industry 5.0: human-centricity, resilience, and sustainability. This approach prioritizes the needs of farmers, empowering them to adapt to a changing environment and ensuring sustainable production.

The application of digital technologies is, therefore, a welcome development for Nigeria's agricultural development, considering the current realities in the country. New digital technologies are being generated; however, the adoption process remains a challenge (Dissanayake *et al.*, 2022).

The introduction of digital technology in Nigeria has been a gradual process, evolving from early computer use for population census data in 1963 to the widespread adoption of mobile technology and the internet. Key milestones include the liberalization of the telecom industry in the early 2000s, the introduction of GSM technology in 2001, and the subsequent rapid increase in internet penetration. The liberalization of the telecom industry and the introduction of GSM technology marked a significant turning point, paving the way for broader digital adoption. The rise of mobile phones and mobile internet access has been a major driver of digital transformation in Nigeria. Furthermore, the growth of financial technology and e-commerce platforms has further accelerated digital adoption, enabling new ways for people to conduct financial transactions and access services online. In summary, the evolution of digital technology in Nigeria has been a dynamic process marked by increasing internet penetration, mobile technology adoption, and the rise of Fintech and e-commerce. While challenges remain, the opportunities for digital technology to drive economic growth and improve the lives of Nigerians are significant.

1. TYPES OF DIGITAL AGRICULTURAL TECHNOLOGY IN NIGERIA.

Sensors

Sensors are one of the main drivers behind the IoT concept, due to advances in technologies that allow reducing their size, as well as making them more intelligent and less expensive [Araújo et al 2021]. In recent decades, wired and wireless sensors have been widely used in the agricultural sector. They play an indispensable role in agricultural activities, by obtaining plant, animal and environmental data and constituting a crucial technology to IoT implementation in agriculture.

Remote Sensor

Remote sensing is the process of gathering information from a distance using devices that are not in close proximity to the things being studied [Araújo, et al 2021]. Among the several uses of remote sensing in agriculture, vegetation indices are crucial instruments for determining the quantity and condition of vegetation by determining whether crop growth is uniform or under stress.

Wireless Sensor (and Actuator) Networks

They have been widely used in several agricultural applications in recent years to enhance traditional farming practices. Networks carry out three fundamental tasks: (a) sensing; (b) communication amongst the network's components; and (c) computation through the use of hardware, software, and algorithms. Conversely, a wireless sensor and actuator network (WSAN) is a variation of WSN that includes an actuator, which is a physical device (such as fans, pumps, valves, lights, irrigation sprinklers, etc.).

Robotic Machines

The use of robots to automate practices in agriculture, including crop scouting (plant monitoring and phenotyping), planting and harvesting, water supply, target spraying, environmental monitoring, weed and pest control, disease detection, pruning, milking, and sorting, has increased interest in this field of robotics in recent years [Fountas et al 2020].

Drones is also known as unmanned aerial vehicles, or UAVs, drones are a key technology that has several use in agriculture and their versatility, ease of use, and ability to collect high-resolution aerial data have made them indispensable tools for modern farming practices. Using drones for crop management and monitoring is one of the most distinctive application in agriculture.Drones, equipped with cameras and sensors of higher quality, improve farmers' ability to photograph fields from above and evaluate crop, insect, and disease conditions as well as fertilizer and irrigation result(Oluwaseun et al 2024)

Internet of connectivity

Connectivity between digital and physical "things" via common and compatible communication protocols is conceptually referred to as the Internet of Things (IoT) [Farooq et al 2020]. Since agricultural operations must be continuously monitored and managed, IoT solutions have been deployed in a number of industries, including healthcare, smart homes, smart cities, and industrial production [Araújo et al 2021]. Agriculture is not an exception to this rule. These include weather forecasting, agricultural management, and soil and water management.

Cloud computing

Today, cloud computing is becoming a commercial Internet-based infrastructure that offers storage, platform, software, hardware, and infrastructure services to a range of Internet of Things applications [offers [Farooq et al 2020]]. Cloud computing has drawn a lot of attention in the agricultural industry in recent decades since it Low-cost data storage services that significantly lower storage costs for agricultural businesses for text, image, video, and other agricultural data. In the context of agriculture, one practical use of cloud computing can be The authors created a cloud-based farm management system that enables the integration of external and internal services and establishes a marketplace of cutting-edge and complex services and applications that end users can access. Since it helps farmers improve agricultural operations on their farms, this system can be considered a crucial instrument in the management of agricultural companies.

Big Data (Analytics)

Despite being in its infancy, recent studies have demonstrated that big data will have a significant impact on the organization and breadth of Agriculture 4.0. It is anticipated that farm management and operations will undergo significant change as a result of utilizing large amounts of data from several sources in real-time and historical data, together with processing, forecasting, and tracking capabilities. This will encourage the ongoing enhancement of business models.

Big data analytics offers doors for other more complicated and uncommon scenarios in addition to more typical ones, such maximizing production yield by determining the best factors (like temperature and rainfall) based on extensive historical, multi-site records Araújo et al 2021. The estimation of food availability in developing nations as a means of tackling the issue of sustainable food security is one example of this [Araújo et al 2021], made possible by the examination of land use and production data from over 13,000 farm households spread across multiple locations in 17 sub-Saharan African countries

Artificial Intelligence (AI)

AI is the most prominent examples of digital technology that is advancing rapidly and presently in use in Nigeria for agricultural activities. Figure 1 depicts the taxonomy of AI technology for farm monitoring and security. AI, especially in the area of machine learning has been recognized as one of the primary forces propelling the adoption of Agriculture 4.0, along with cloud computing and the Internet of Things. According to recent studies, machine learning (ML) is one of the most promising approaches being investigated in this area It has applications in the fields of weather and climate change, crop and animal monitoring and management, weeds, soil, and food supply and security. Mmanagement [Shi, et al 2019] as well as climate change and weather. Due to their ability to recognize intricate patterns, trends, and relationships in multidimensional, heterogeneous agricultural data, generate precise predictions, and offer a solid basis for enhanced agricultural decision-making and operations management, machine learning algorithms have been used to maximize crop yield and minimize input costs [Shi, et al 2019]. Others include virtual reality, 3d modelling, data mining and real time collaboration.

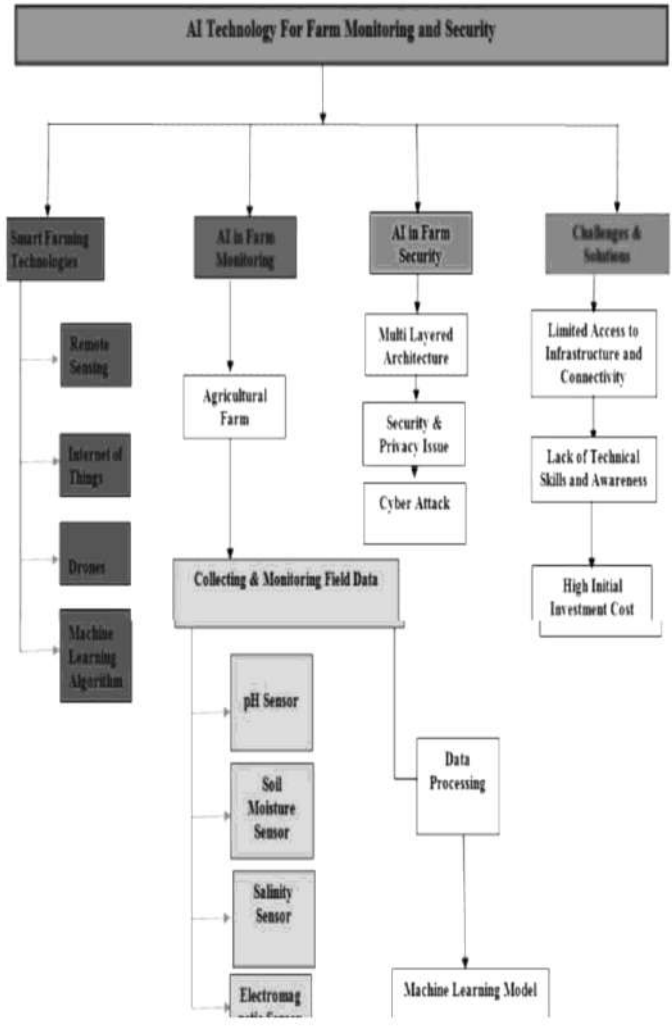


Fig. 1: Taxonomy of AI Technology For Farm Monitoring and Security. Source/Adopted from oluwaseun *et al* 2024

Digital Platforms Available to Nigeria Farmers

The agricultural sector in Nigeria is undergoing a dynamic and transformative shift, fueled by the growth of digital platforms that are connecting buyers and producers along the whole agricultural value chain (Figure 2). According to reports, $63 million was reportedly spent on agricultural technologies in Africa in 2019. About 60% of the investment and operational startups were in Kenya, Nigeria, and Ghana. Nigerian agricultural technology companies use digital solutions to increase farmers' access to markets, financing, assets, and data-driven information (Raithatha, 2020). Agricultural technology firms are fast offering innovative technology solutions to farmers. This brings to the fore the issues of awareness and adoption of these technological solutions by farmers. The marketing, trading, and distribution of agricultural products are being completely transformed by these platforms, which are driven by technology advancement. Furthermore, it is designed to make searching for agro-products available at your fingertips. They are dynamic online market place dedicated to agriculture related activities ensuring farmers, buyers and sellers of agricultural products have direct contact with other agro-allied providers and manufacturing industries around the world. They are digital agro-platform connecting farmers to buyers of agro-produce.

(i) **ComX by AFEX** and Associated Foreign Exchange. (AFEX): is a commodities exchange platform for people to trade in agricultural commodity instruments. To help farmers have more negotiating power, AFEX generates tradeable electronic warehouse receipts that can be used as money. It also provides services like connecting farmers with agronomic training, input access, and loans. To enhance farmers' productivity, In order to create a warehouse receipt system in collaboration with the FMARD, AFEX was established in 2014. The method made it possible for cooperatives and smallholder farmers in four Nigerian states to securely store their produce in authorized warehouses and to utilize receipts as security for loans. 26–(ii) AFEX expanded on the success of this project to become a platform for trading commodities and also took part in the ABP as an aggregator. It is a digitally enabled marketplace that brings commodities into a financial market

environment, enabling ease of transactions and eliminating concerns around storage and other commodity associated with costs.

Company	Founded	Use cases	Cumulative users*
AFEX	2014		106,000
AgroMall	2016		530,000
BeatDrone	2015		300
Crop2Cash	2018		1,000
FarmCrowdy	2016		25,000
Hello Tractor	2014		5,000
Thrive Agric	2016		22,000
TradeBuza	2018		2,000
Verdant AgriTech	2014		8,000

Figure 2: Digital Platforms Available to Nigeria Farmers

(ii)AgroMall is a significant player in this changing environment as well. It is a comprehensive digital platform that serves as a bridge connecting farmers and other agricultural value chain partners. AgroMall creates economic identities for farmers using farmer data. Farmers may access vital resources including market data, financial services, and agribusiness prospects thanks to AgroMall's holistic approach.

Farmers can advertise their goods and establish connections with prospective customers through its online marketplace, increasing their market reach (AgroMall, n.d.). The financial services offered by the platform also improve farmers' access to loans and operating capital, facilitating a more seamless flow of agricultural operations.

In 2017, AgroMall also took part in the ABP as a service provider. AgroMall, which was established in 2016, gives farmers access to input credit and enables them to open a bank account by providing them with a digital profile that includes the geo-coordinates of their farmlands. Farmers can obtain input loans from participating financial service providers (FSPs) registered under the ABP by using these bank accounts and digital profiles. Additionally, when farmers sell their commodities at aggregation centers, they can get market-rate payments that are deposited into their new bank accounts. While AFEX and AgroMall expanded by participating in government-led programs, other businesses and entrepreneurs have been able to start and expand without the direct assistance of the government. New digital solution have as a result of this.

(iii)FarmCrowdy: Farmcrowdy, which provide platforms for public investment in agribusiness. This ground-breaking platform, which combines technology and agriculture in a seamless manner, is at the vanguard of this digital revolution. Farmers, who are frequently limited in their access to markets and capital, find solace in FarmCrowdy's approach. Through the platform's crowdfunding model, anyone may directly assist farmers and sponsor agricultural projects. By giving them much-needed funding for post-harvest operations, automation, and inputs, this mutually beneficial partnership empowers farmers (FarmCrowdy, n.d.).

(iv) Babban Gona, which translates to "Great Farm" in the local tongue, lives up to its name by encouraging excellence among smallholder farmers. This cutting-edge platform offers a full ecosystem of support, going beyond traditional market linkage strategies. Babban Gona provides farmers with assured markets for their produce, loans, and training (Babban Gona, n.d.). The platform increases farmers' bargaining power and guarantees a market by linking them with bulk buyers and processors.

(v) Hello tractor: Hello Tractor uses an online platform to connect tractor owners and smallholder farmers. By bringing together farmers and tractor owners, Hello Tractor is transforming agricultural practices in the field of mechanized farming. This mobile platform reduces the labor-intensive aspect of traditional farming by enabling farmers to get tractor services whenever they need them (Hello Tractor, n.d.). Hello Tractor supports effective agriculture and maximizes output by fusing technology and equipment.

(vi) **Farm.ng:** Farm.ng is an e-commerce platform that removes middlemen for farmers looking for a direct path to customers. Farmers can advertise their goods on this online marketplace and communicate with customers directly(farm.ngn.d). The platform makes use of technology to enable smooth transactions, guaranteeing prompt and effective fresh produce distribution. Farm.ng strengthens market ties and gives farmers the ability to establish competitive pricing for their goods by providing direct access to consumers.

(vii) **Farmsquare:** is an online agricultural store that provides quick farm market solutions for farmers, agro-dealers with an excellent shopping experience.

(viii) **Afrimash:** is an eCommerce marketplace for agricultural items where you canshop conveniently and securely for quality items and receive your order safely at your location.

(ix) **Thrive Agric**: links farmers to finance, and access to local & global markets for their commodities; towards ensuring food security for all. Thrive Agric provide platforms for public investment in agribusiness.

(x)**Agric fintech:** is another digital agriculture platform that provides smallholder farmers with financing, aggregation, food processing and trading and insurance.

(xi) **Bellefu-agrofoods:** is an online raw food shopping mart that connects farmers to buyers.

(xii) Verdant AgriTech: provides farmers with a mobile-based digital solution that offers market information, managerial support, and market access for smallholder farmers.

(xiii) TradeBuza: is another cloud-based web and mobile-based platform that assists clients in managing the visibility of their out-grower schemes and trading commodities more effectively.

(xiv) BeatDrone: uses drones for pesticide spraying, crop monitoring, and farmland mapping.

(xv) Zenvus: A digital technology device that measures and analyzes soil data like temperature, nutrients and vegetative health.

(xvi) Agrikore: is a blockchain based smart-contracting, payments and marketpace system that ensures that everyone in agriculture(Farmers, FMCGs, Agriculture inputs providers, produce aggregators, insurance companies, financial institutions, governments, development partners) can do business with each other in a trusted environment.

(xvii) Crop2Cash: digitizes the entire value chain and offers digital payments.

AgrIDS framework, eSagu system and computer vision automated sorting systems are other examples of agricultural digital systems in Nigeria. These tools enhance agricultural productivity, offering professional guidance, and improving the distribution of agricultural goods and services Utilizing state of the art sensor and analysis techniques, Nigeria's agricultural digital system influences crop yields by increasing agricultural yields, supporting management choices, increasing output, reducing labor hours, and ensuring effective control of fertilizer and irrigation systems. Nigerian food security might be greatly enhanced by precision agriculture, which also propels the country's agricultural industry toward modernization while effectively satisfying consumer demands. Nigerian workers' productivity and crop yields can be raised by implementing precision agriculture technologies like drones, remote sensing, and artificial intelligence (Oluwarotimi and Oluwadamilola, 2022).

2. IOT APPLICATIONS IN NIGERIAN AGRICULTURE

Precision Farming IoT; IoT makes precision farming possible by giving real-time information on crop health, weather patterns, and soil characteristics.

The sensors track and measure several farm variables that impact production, such as soil nutrients, meteorological information, soil moisture, and temperature. Enabled sensors gather information on temperature, nutrient levels, and soil moisture, enabling farmers to apply fertilization and irrigation for higher yields and resource savings. Relative humidity, solar radiation, atmospheric pressure, rainfall, leaf wetness, chlorophyll, wind speed, dew point temperature, wind direction, and air and soil temperatures at different depths are all measured by these sensors.

In Nigeria, Hello Tractor, an agritech business dedicated to enhancing food and economic security across sub-Saharan Africa, has introduced mechanization services by connecting smallholder farmers with smart tractor services through an Internet of Things-based platform. GPS and Internet of Things sensors were installed on the tractors to track performance and usage. Because farmers could more effectively cultivate bigger areas with this approach, access to mechanization services enhanced farm productivity by 40%. However, using IoT-enabled smart tractors optimized fuel use and cut greenhouse gas emissions by 15%, which helped to promote more environmentally friendly agricultural methods (Hello Tractor, 2021).

In Nigeria, precision agriculture has been in a continuum development to tackle the variability of soil and crop conditions on farmland. To ensure that farm families are utilising technologies that increase profits while reducing risks of input waste in farming. Also, to address the problem of misuse of agricultural land, inconsistency, and unsustainability while increasing productivity. Precision agriculture affects productivity and facilitates other tertiary agriculture activities, including marketing the farm proceeds for farm families in Nigeria (Ezeaku et al., 2024).

Livestock Monitoring; ; IoT applications are also used in livestock husbandry, where sensors can detect movement, optimize feeding schedules, and keep an eye on animal health. Wearable technology can give farmers information on behavior and vital signs, enabling them to identify health problems early and enhance herd management in general.

IoT devices with GPS and health sensors monitor the whereabouts, condition, and behavior of cattle, allowing for improved management and prompt responses.

The kinds of animals being examined determine which livestock component needs to be tracked. By using RFID technology to tag each animal, the deployment and implementation solution also enables farmers to track and inquire about the whereabouts of their livestock, avoiding animal theft. Data from monitoring other areas, such storage monitoring of fuel, water, and animal feed, can help farmers plan ahead and save money. For instance, the conductivity of cow and buffalo milk can reveal details about the animals' health. Temperature, humidity, yield, pest attack, and water quality are other influences IoT is also applied in asset tracking as it is used in livestock monitoring to improve companies supply chain and logistics.

Drought monitoring; Using Internet of Things solutions, farmers can detect water shortages before they become severe problems. Additionally, some systems can provide information on the best times and locations for crop irrigation, allowing farmers to maximize their watering efforts. Monitoring soil and nutrient levels would streamline agricultural production processes and lead to valuable water savings, particularly in specific geographical regions. This can be achieved through the implementation of smart irrigation systems (Xin and Tao 2020). The application of IoT technologies in the agricultural sector has the potential to revolutionize current production procedures in agriculture. The impact of IoT in agriculture has been significant, considering the wide range of applications we have explored above. Figure 2 represents the mechanism IoT can improve agricultural efficiency, broken down into several key components and mechanisms.

Automated Irrigation Systems; IoT-based automated irrigation systems have the potential to optimize water consumption by supplying the appropriate quantity of water at the appropriate moment. Water conservation and crop health are enhanced by these systems, which use weather data and soil moisture sensors to predict irrigation.

Automated Irrigation and Resource Management

Automation of agriculture with artificial intelligence already improves production, harvesting, and processing (Dawn et al., 2023),

Irrigation is crucial for agricultural development, especially in dry and semiarid regions, because without it, there is a high likelihood of crop failure or a significant decrease in yield . In view of this, we must develop a strategic plan for efficient water supplies and irrigation systems to function effectively in Nigeria. The primary goal of constructing an irrigation system is to minimize resource use and boost efficiency. Temperature and moisture sensors may be employed at a time to optimize the frequency of watering and will reduce human error, saving time and labour. Several methods are employed in modern irrigation systems to optimize water use efficiency. AI-powered sensor-based automatic irrigation systems.

Crop Monitoring and Disease Management; Drones equipped with IoT technology capture high-resolution images of crops, identifying diseases and nutrient deficiencies for targeted interventions. This involves an automatic disease detection using the leaf or the general well-being of crop under investigation (Thorat et al., 2017). Remote sensors and drones are examples of IoT technologies that can monitor crop conditions and identify early warning indications of insect infestations or disease. Crop losses are decreased and prompt intervention is made possible. For example, cameras with image recognition algorithms can detect plants under stress and notify farmers.

Weather Forecasting; Forecasting the Weather Farmers can make well-informed decisions regarding planting, irrigation, and harvesting thanks to real-time weather data provided by IoT-based weather stations. The acquisition of such data aids in the comprehension of farm processes and patterns. Wetness of the leaves, temperature, humidity, soil moisture, salinity, climate, dry circle, sun radiation, pest movement, human activities, and rainfall are examples of such data (Zhao et al., 2010). Having such a thorough record makes it possible to make the best decisions possible to raise farm produce quality, reduce risk, and increase profitability. Moreover, reliable and timely weather forecasting information about rainfall and climate changes might raise productivitY.

RemoteField Monitoring; IoT makes it possible to remotely monitor agricultural fields, which is especially useful for big farms or places with poor access. Using mobile applications, farmers can keep an eye on their crops from any location and get real-time information and notifications about important conditions that need to be attended to. (Sundmaeker et al., 2016)

Accurate data analysis IoT-based solutions in agriculture have opened up a wide range of practical applications, such as crop data analysis, a and statistics, providing precise and reliable results.

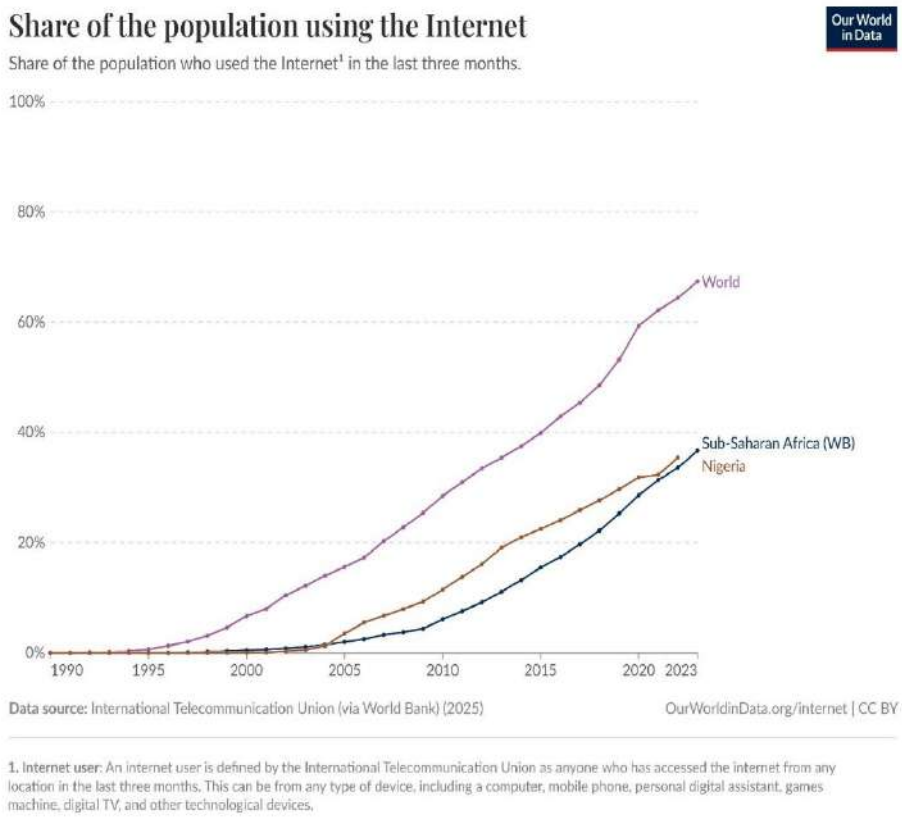
Accurate data analysis (Data-Driven Decision); Making Farmers can gain useful insights from the analysis of the massive volumes of data generated by IoT. Crop production predictions, planting schedule optimization, weather forecasting, and pest detection and the optimal practices for certain conditions may all be achieved with advanced analytics and machine learning. . These solutions utilize machine learning, cloud technology, and artificial intelligence to analyze data and This data-driven strategy can greatly improve sustainability and productivity.

Figure 2: The mechanisms IoT improves agricultural efficiency;Sources Adopted from Duguma e*t al* 2024

2.1 Digital Extension Technology in Nigeria

One important industry with amazing potential for overcoming the challenges of achieving a nation's financial development, poverty reduction, food security, wealth creation, and employment is agriculture.

The agricultural industry employs more than 60% of the working population, produces on average over 40% of GDP, and has the potential to reduce poverty more than any other sector in the majority of third-world nations, such as Nigeria



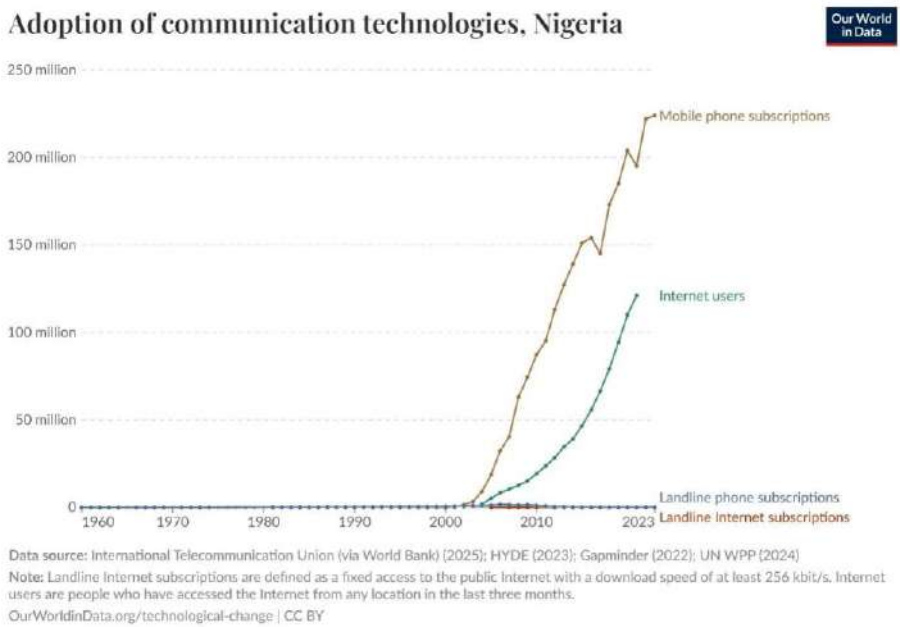
Adoption of Communication Technologies, Nigeria

The graph illustrates the rapid growth of communication technologies in Nigeria from 1960 to 2023. Mobile phone subscriptions expanded dramatically after 2000, surpassing 200 million by 2023. This surge reflects Nigeria's liberalization of the telecommunications sector, particularly following the introduction of GSM networks in 2001.

Similarly, Internet usage grew steadily, especially after 2010, reaching over 100 million users by 2023. Mobile internet, rather than fixed broadband, has been the dominant mode of access, driven by increasing smartphone penetration and the expansion of mobile networks (GSMA, 2023).

In contrast, landline phone and landline internet subscriptions remained flat and negligible, highlighting Nigeria's leapfrogging from limited fixed-line infrastructure directly to mobile technologies (ITU, 2023). This mobile-first digital transformation has had profound implications for agriculture, education, healthcare, and commerce, particularly in rural areas historically underserved by fixed-line infrastructure.

Nevertheless, significant challenges remain. Despite the large number of users, internet access quality—particularly in terms of speed, affordability, and reliability—continues to vary widely across the country, posing barriers to full digital inclusion (World Bank, 2022).



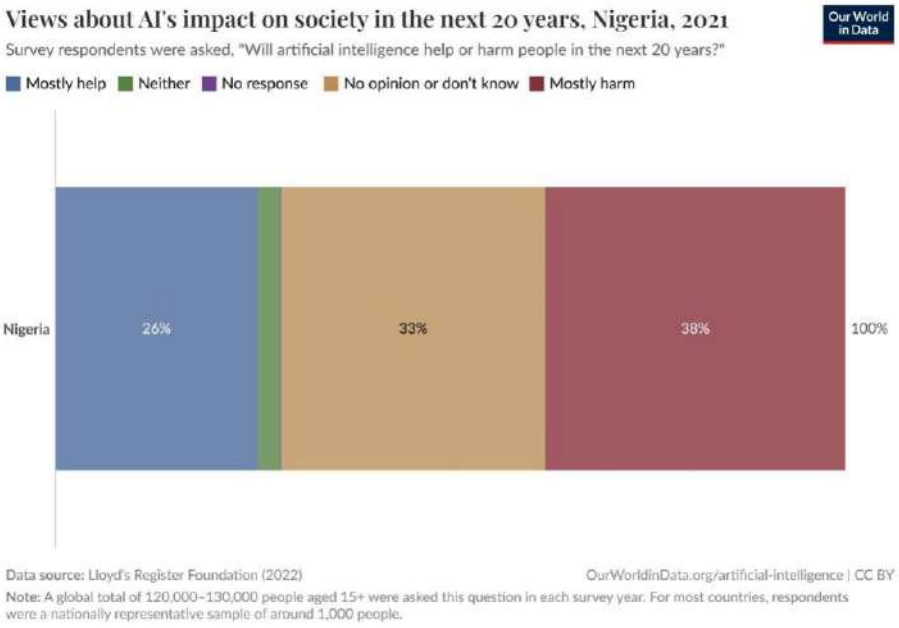
The chart presents Nigerians' views on the future impact of artificial intelligence (AI) over the next 20 years. It shows that 38% of respondents believe AI will mostly harm society, while 26% think AI will mostly help.

Additionally, 33% of the population expressed no opinion or stated they don't know. The small fraction of respondents who selected "neither" or gave no response further reflects uncertainty.

This distribution reveals both optimism and anxiety toward AI technologies in Nigeria. The high percentage of people expecting harm mirrors global concerns that AI could increase unemployment, deepen inequalities, and exacerbate ethical issues (Miao, *et al.,* 2021). In particular, the fear of job automation is strong in many developing economies, where labour markets are more vulnerable to technological disruptions (World Bank, 2019).

Meanwhile, the 26% who are hopeful see AI's potential in boosting sectors like healthcare, agriculture, finance, and education sectors where emerging technologies are already improving efficiency and access. However, the large proportion (33%) expressing uncertainty signals a major gap in digital literacy and public understanding of AI in Nigeria. Studies have shown that in lower- and middle-income countries, limited awareness and digital divide issues contribute heavily to scepticism and fear of new technologies (Miao, *et al.,* 2021).

As Nigeria and similar countries continue to adopt AI and digital innovations, public education, regulatory frameworks, and ethical guidelines will be critical to maximizing AI's benefits while minimizing its risks (Our World in Data, 2022).


Views about AI's impact on society in the next 20 years, Nigeria, 2021
Our World in Data
Survey respondents were asked, "Will artificial intelligence help or harm people in the next 20 years?"
Mostly help
Neither
No response
No opinion or don't know
Mostly harm
Nigeria
26%
33%
38%
100%
Data source: Lloyd's Register Foundation (2022)
OurWorldinData.org/artificial-intelligence | CC BY
Note: A global total of 120,000–130,000 people aged 15+ were asked this question in each survey year. For most countries, respondents were a nationally representative sample of around 1,000 people.

Share of population in range of mobile network by capability of Nigeria

The chart from *Our World in Data* (2025) illustrates the progression of mobile network coverage in Nigeria from 2015 to 2022, focusing on the availability of 2G, 3G, and 4G networks. It measures the share of the population living within range of each type of mobile signal, irrespective of whether or not individuals actually use mobile phones. The graph highlights important trends in Nigeria's digital connectivity and the gradual upgrade of mobile infrastructure over time.

The 2G network, which enables basic voice calls and text messaging, has maintained a high level of coverage throughout the period. Starting at around 90% of the population in 2015, it shows only slight fluctuations, remaining consistently above 85% and approaching 90% again by 2022. This stability suggests that 2G infrastructure had already been largely built out before 2015 and continues to serve remote and rural areas where newer networks may not yet be fully established (ITU, 2020).

The 3G network, which supports more data-intensive services like internet browsing and multimedia messaging, saw substantial expansion between 2015 and 2018. Coverage grew from about 40% in 2015 to over 70% by 2018. However, after 2018, the rate of growth slowed, and coverage plateaued around 70–75% through to 2022. This plateau might reflect strategic shifts by telecom providers toward investing more heavily in newer technologies like 4G, rather than further expanding 3G in areas already being targeted for upgrades (GSMA, 2021).

Most notably, the 4G network, which offers significantly faster internet speeds, has experienced rapid growth. From less than 25% coverage in 2017, it rose dramatically to about 80% by 2022. This indicates an aggressive push by service providers to upgrade network infrastructure and expand high-speed connectivity across Nigeria. Such growth in 4G coverage is crucial for enabling a broader digital economy, supporting mobile banking, e-learning, telemedicine, and other internet-dependent services critical for development (World Bank, 2016).

Challenges to Digital Utilization

(i) Limited Access to Infrastructure and Connectivity: the channel confound caused by inadequate infrastructure and connectivity mostly realized in rural setting where majority of the farmers are situated can be addressed. The implementation of digital technology in agriculture necessitates the availability of water, consistent electricity, dependable internet connectivity, and well-equipped research labs. In the agricultural sector of Nigeria, the absence of certain infrastructure may make it difficult to implement DT.A lhassan et al. (2020) have pointed out that; this is because, for applied benefits of AI to realize their independent potential for improving decision-making, resourcing decisions, and productivity enhancement, there is needed to desirable infrastructure and connectivity

(ii) Lack of Technical Skills and Awareness: ,farmers may be reluctant to adopt AI technology, fearing complexity or uncertainty about its effectiveness and operation and Furthermore not many people are aware of the potential advantages of AI in enhancing farming methods and raising yields.(. Without adequate training and awareness-raisingWithout adequate training and awareness-raising initiatives

(iii) Lack of Collaborative Effort: The application of Digital Technologies entails the cooperation of researchers from various disciplines and extends from early design to decommissioning. For DT to be implemented successfully, certain skills are needed, including data scientists, engineers, agricultural and animal scientists, developers and programmers, and business analysts. To be able to contribute to the growth of DT in the Nigerian agriculture sector, individuals having this understanding are required.

(iv) High Initial Investment Costs: Due to the high initial investment requirements, many Nigerian farmers, particularly smallholders with limited resources, find it challenging to incorporate AI technology into their farming practices. Limited t access to affordable financing options and incentives to offset initial investment costsa farmers may be unable to adopt AI-driven solutions, limiting their potential to enhance productivity and competitiveness and Investments in sensors, software, hardware, and data analytics platforms are frequently needed for AI-

driven solutions, in addition to continuing technical support and maintenance.

CONCLUSIONS

Agriculture development over the years can be seen that digital technologies and data-driven techniques have the potential to transform agriculture more precisely, efficiently, and sustainably. Furthermore, while providing greater transparency for consumers on how food is produced, decision-making support has helped farmers in many practices, in terms of environmental and agricultural performance. Beyond farming, while digital technologies make the job more attractive to new generations, they offer many opportunities to reduce problems related to remoteness and improve access to services.

Technologies like the internet of things, cloud computing, big data, artificial intelligence, drones, and robotics provide making processes more efficient and drive the creation of new products and services and streamline agricultural operations. Technological innovations can help us overwhelm many of the economic, social, and environmental challenges that agriculture is facing today amnd there are many smart farming technologies including decision support system, yield monitoring, smart irrigation, smart spraying, management of crop disease, crop monitoring, soil monitoring, treatment of pests with robots, intelligent harvesting according to maturity, traceability from farm to fork, logistics, as well as e-marketing.

However the use of digital technologies is still very low compared to the rest of the world and can be attributed to the challnges such as limited access to infrastructure and connectivity,lack of technical skills and awareness and high initial investment cost.

REFRENCES

Abubakar, A. D., Oladimeji, Y. U., Ahmed, B., Sanni, S. A., Umar, M., Hussaini, A. S., Magaj, B. D., & Sani, A. A. (2024). Assessing sustainability of government- and farmer-managed irrigation programmes for vegetable producers in north west Nigeria. J. Arid Agric., 25 (3): 64-74

AgroMall. (n.d.). Enabling value. Retrieved from https://www.agromall.com/

Ahmad L & Nabi F (2021). Agriculture 5.0. CRC Press, London

Aker, J. C., & Mbiti, I. M. (2010). Mobile phones and economic development in Africa. *Journal of Economic Perspectives, 24*(3), 207-232. https://doi.org/10.1257/jep.24.3.207

Araújo, S.O.; Peres, R.S.; Barata, J.; Lidon, F.; Ramalho, J.C. 2021Characterising the Agriculture 4.0 Landscape—Emerging Trends, Challenges and Opportunities.Agronomy 2021, 11, 667. https:// doi.org/10.3390/agronomy11040667

Babban Gona. (n.d.). Our impact. Retrieved from https://www.babbangona.com/

David, C. R., Mondira, B., Auvikki de Boon, R. D., & Price, C. (2022). The Fourth Agricultural Revolution: past, present, and future. Edward Elgar Publishing, Cheltenham, UK, pp. 151-174. Available at https://centaur.reading.ac.uk/99800/

Dissanayake, C.A.K., Jayathilake, W., Wickramasuriya, H.V.A., Dissanayake, U., Kopiyawattage, K.P.P. and Wasala, W.M.C.B. (2022), "Theories and models of technology adoption in agricultural sector", Human Behavior and Emerging Technologies, Vol. 2022, 9258317, doi: 10. 1155/2022/9258317

Ezeaku, C., Ani, A. O., Adama, J., Job, V., Sule, S., Onwualu, A., Nwankwojike, B., Otoijamun, I., & Ogbobe. P. (2024). Willingness to adopt precision agriculture: An analysis of Gombe and Bauchi States of Nigeria. *Nigerian Journal of Technology*, 43(1). Pp.198 – 206. https://doi.org/10.4314/njt.v43i1.21

FarmCrowdy. (n.d.). Empowering farmers, creating value. Retrieved from https://www.farmcrowdy.com/

Farooq, M.S.; Riaz, S.; Abid, A.; Umer, T.; Zikria, Y.B.(2020) Role of IoT Technology in Agriculture: A Systematic Literature Review. Electronics 9, 319 http://dx.doi.org/10.3390/electronics9020319

Folorunso, O.; Ojo, O.; Busari, M.; Adebayo, M.; Joshua, A.; Folorunso, D.; Ugwunna, C.O.; Olabanjo, O.; Olabanjo, O. Exploring Machine Learning Models for Soil Nutrient Properties Prediction: A Systematic Review. Big Data Cogn.Comput. 2023, 7, 113. https

Fountas, S.; Mylonas, N.; Malounas, I.; Rodias, E.; Hellmann Santos, C.; Pekkeriet, E. (2020,) Agricultural Robotics for Field Operations.Sensors20, 2672. http://dx.doi.org/10.3390/s20092672

GSMA. (2021). The mobile economy: Sub-Saharan Africa. *GSMA Intelligence Report*. https://www.gsmarena.com/network-bands.php3?sCountry=NIGERIA

GSMA. (2023). The mobile economy: Sub-Saharan Africa. *GSMA Intelligence*. https://www.gsma.com/mobileeconomy/sub-saharan-africa/

Hello Tractor. (n.d.). Agricultural equipment sharing & farm data insights. Retrieved from https://www.hellotractor.com/

International Telecommunication Union. (2023). Measuring digital development: Facts and figures. *ITU Report*. https://www.itu.int/en/ITU-D/Statistics/Pages/facts/default.aspx

Isah U. S. 2022. Adoption of Agricultural Technologies: *How Far Have Farmers Gone? Inaugural Series 99*, University of seminar and colloquium committee Federal University of Technology, Minna. 56pp.

ISPA (2021). Precision Ag Definition. International Society of Precision Agriculture Retrieved in July, 29, 2021 from https://www.ispag.org/about/definition

Liu Y, Ma X, Shu L, Hancke G P, Abu-Mahfouz A M (2021). From Industry 4.0 to Agriculture 4.0: Current Status, Enabling Technologies, and Research Challenges. IEEE Transactions on Industrial Informatics, 17(6): 4322-4334. https://doi.org/10.1109/TII.2020.3003910

Miao, F., Holmes, W., Huang, R., & Zhang, H. (2021). AI and education: Guidance for policy-makers. *UNESCO*. https://doi.org/10.54675/PCSP7350

Mohapatra, B., Tripathy, S., Singhal, D. and Saha, R. (2022) "Significance of digital technology in manufacturing sectors: examination of key factors during COVID-19", Research in Transportation Economics, 93, 101134.

Nnamonu, C. U., Ejimonye, J. C., & Omaliko, J. C. (2021). Exploring food security and poverty reduction in Nigeria. British International Journal of Education and Social Sciences, 8(2), 1-10. ISSN (3342 – 543X);

Oluwadamilola, & Oluwarotimi. (2022). *Journal of Digital Food Energy Water Systems 3 no*. https://journals.uj.ac.za/index.php/DigitalFoodEnergy_WaterSystems/article/view/2269

Our World in Data. (2025). Mobile and landline phone subscriptions per 100 people. *Our World in Data Report*. https://ourworldindata.org/grapher/mobile-landline-subscriptions

PricewaterhouseCoopers Nigeria(2021),PwC network.

Raithatha, R. (2020), "AgriTech in Nigeria Investment opportunities and challenges", availableat:https://www.gsma.com/mobilefordevelopment/wpcontent/uploads/2020/04/AgriTech_in_ Nigeria_Investment_Opportunities_and_Challenges1.pdf (accessed 15 September 2022)

Saiz-Rubio, V., & Rovira-Más, F. (2020). From Smart Farming towards Agriculture 5.0: A Review on Crop Data Management. *Agronomy*, *10*(2),207. https://doi.org/10.3390/agronomy10020207

Sennuga, S. O., Fadiji, T. O., & Thaddeus, H. (2020). Factors Influencing Adoption of Improved Agricultural Technologies (IATs) among Smallholder Farmers in Kaduna State, Nigeria Int. J. Agric. Educ. Ext. 6(2), 382-391. www.premierpublishers.org. ISSN: 2167-0432

Shi, X.; An, X.; Zhao, Q.; Liu, H.; Xia, L.; Sun, X.; Guo, Y.(2019) State-of-the-art Internet of things in protected agriculture. Sensors 2019, 19, 1833. http://dx.doi.org/10.3390/s19081833

Sturgeon, T., Fredriksson, T. and Korka, D. (2017), "The 'New' digital economy and development", UNCTAD Technical Notes on ICT for Development, 8

Thorat, A., Kumari, S., & Valakunde, N. D. (2017). An IoT based smart solution for leaf disease detection. *2017 International Conference on Big Data, IoT and Data Science (BID) (193- 198). IEEE.*

CHAPTER 3
ARTIFICIAL INTELLIGENCE AND SUSTAINABLE AGRICULTURE: ENHANCING PRODUCTIVITY, RESILIENCE, AND FOOD SECURITY

[1]Assoc. Prof. Neha VERMA

[1]Swami Vivekanand Subharti University, dr.neha2917@gmail.com, ORCID ID: 0000-0003-2540-9876

INTRODUCTION

Agriculture remains the backbone of human civilization and an essential sector for economic development, food security, and rural livelihoods. With the global population projected to reach nearly 10 billion by 2050, agricultural production must increase substantially to meet rising food demand. Traditional agricultural practices alone are insufficient to achieve the required productivity increases while conserving natural resources and addressing environmental concerns. Hence, there is a growing emphasis on integrating digital technologies—particularly Artificial Intelligence (AI)—to revolutionize farming. AI refers to computational systems that perform tasks requiring human intelligence, such as pattern recognition, decision-making, and predictive analysis. In agriculture, AI interprets large volumes of data from diverse sources—such as satellite imagery, IoT sensors, and drones—to guide optimal farming practices, reduce input waste, and enhance productivity and resilience to climate shocks. The potential of AI in agriculture aligns with key global goals, especially SDG-2 (Zero Hunger), SDG-13 (Climate Action), and SDG-12 (Sustainable Consumption and Production). Yet, realizing AI's potential requires addressing technical, economic, and policy challenges that hinder equitable adoption—particularly among smallholder farmers in developing countries.

Agriculture stands at a critical crossroads in the 21st century. The sector is under immense pressure to increase productivity to feed a growing global population, projected to reach nearly 10 billion by 2050, while simultaneously confronting the adverse impacts of climate change, land degradation, and resource scarcity. Traditional agricultural practices alone are no longer sufficient to cope with these multidimensional challenges; there is a pressing need for transformative solutions that enhance sustainability, efficiency, and resilience (Ali et al., 2025). Within this context, Artificial Intelligence (AI) emerges as a powerful technological force with the potential to fundamentally redesign agricultural systems and accelerate progress toward global food security. AI refers to computational systems capable of learning from data, recognizing patterns, and making decisions with minimal human intervention.

In agricultural applications, AI leverages machine learning, deep learning, computer vision, robotics, and predictive analytics to support precision farming, optimize input use, and improve adaptive responses to environmental changes (Ali et al., 2025; Somashekar et al., 2024). By converting large volumes of data from sensors, satellite imagery, and weather forecasts into actionable insights, AI enables farmers and policymakers to make informed decisions that enhance productivity while minimizing environmental impacts. Recent research highlights the transformative impact of AI on sustainable agriculture. For example, machine learning and deep learning techniques have been used to enhance crop yield prediction, detect pests and diseases with high accuracy, and optimize irrigation schedules—leading to productivity gains and reductions in water and chemical inputs (Ali et al., 2025; Somashekar et al., 2024; Roy et al., 2025). Moreover, AI-enabled climate-smart agricultural tools can forecast environmental risks, support adaptive cropping strategies, and bolster resilience against extreme weather events, thereby reinforcing food system stability (Roy et al., 2025). These capabilities align directly with global development goals such as SDG-2 (Zero Hunger) and SDG-13 (Climate Action), underscoring the role of AI in achieving sustainable and resilient agricultural landscapes. AI adoption in agriculture is uneven globally, constrained by barriers such as high implementation costs, limited digital infrastructure, and challenges in technical capacity among smallholder farmers. To realize the full potential of AI in fostering sustainable agriculture, it is critical to address these constraints through inclusive policymaking, investment in rural digital ecosystems, and capacity building (Ali et al., 2025; Roy et al., 2025). This chapter explores how AI technologies enhance productivity, strengthen resilience, and contribute to food security, drawing on empirical evidence and recent research to illustrate pathways for integrating AI into sustainable agricultural systems.

Agriculture remains fundamental to human survival, economic development, and rural livelihoods. However, the sector is under unprecedented pressure. The global population is projected to approach 10 billion by 2050, requiring significant increases in food production while natural resources decline and climate variability intensifies (Food and Agriculture Organization [FAO], 2022).

Traditional agricultural practices alone cannot meet this demand without exacerbating environmental degradation. Consequently, the integration of digital technologies—particularly Artificial Intelligence (AI)—has emerged as a transformative pathway for sustainable agricultural development.

AI refers to computational systems capable of learning from data, recognizing patterns, and making decisions with minimal human intervention. In agriculture, AI processes large datasets from remote sensing platforms, Internet of Things (IoT) sensors, weather models, and farm equipment to support precision management (Srikanthnaik, 2024). These capabilities allow farmers to optimize irrigation, fertilization, pest control, and harvesting decisions, thereby enhancing productivity and reducing waste.

The relevance of AI extends beyond productivity. Climate change introduces uncertainties in rainfall patterns, temperature regimes, and pest dynamics. AI-driven predictive analytics can anticipate environmental risks and guide adaptive strategies, improving resilience (Evans & Raja, 2024). Thus, AI supports a transition from resource-intensive farming toward sustainable intensification, aligning agricultural development with SDG targets.

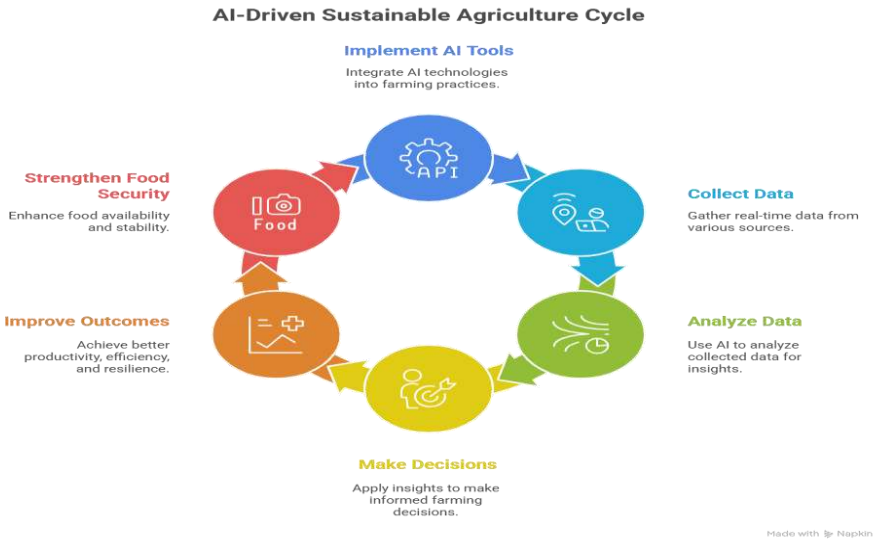


Figure 1- AI-Driven Sustainable Agriculture Cycle

Sustainable agriculture balances three pillars: economic viability, environmental protection, and social equity. AI functions as an enabling layer that enhances decision-making across these dimensions.

AI as a Decision-Support System

AI systems synthesize multi-source data into predictive models that inform farm-level and policy-level decisions. Machine learning (ML) algorithms analyze historical yield, soil, and weather data to forecast crop performance. Computer vision interprets imagery for disease detection, while robotics automates labor-intensive operations (Hasan et al., 2022).

Sustainable Agriculture Cycle

AI contributes to a continuous cycle: Data collection → Predictive analytics → Precision intervention → Resource efficiency → Enhanced productivity → Environmental sustainability → Food security.

This cycle demonstrates how AI links technological inputs to socio-environmental outcomes.

AI Technologies in Agriculture

Key technological components include:

Technology	**Agricultural Role**
Machine Learning	Yield forecasting, disease prediction
Computer Vision	Crop health monitoring
Robotics	Autonomous planting and harvesting
IoT Sensors	Soil and climate monitoring
Big Data Analytics	Integrated decision systems

These technologies form the infrastructure for precision agriculture (Srikanthnaik, 2024).

AI and Agricultural Productivity

Empirical evidence indicates that AI-enabled precision agriculture improves yields and reduces input waste. ML-based irrigation scheduling improves water-use efficiency while sustaining yields (Efremova et al., 2019).

Precision nutrient application reduces fertilizer overuse and improves soil health. AI-driven disease detection tools enhance early intervention, lowering crop losses (Barbedo, 2025).Productivity gains occur through:

- Optimized input timing
- Reduced pest damage
- Improved crop monitoring
- Mechanization efficiency. These gains contribute to sustainable intensification, where output increases without proportional resource expansion (FAO, 2022).

Resource Use Efficiency and Environmental Sustainability

AI enhances sustainability by minimizing excess input use. Smart irrigation systems apply water based on soil moisture data, reducing wastage (Efremova et al., 2019). Targeted pesticide application through computer vision reduces chemical runoff. AI thus mitigates greenhouse gas emissions, soil degradation, and biodiversity loss.Environmental benefits include:

- Lower water withdrawal
- Reduced agrochemical pollution
- Improved soil nutrient balance

These outcomes align with SDG 12 on responsible production.

Climate Resilience and Risk Management

Climate variability threatens food systems. AI predictive models integrate climate forecasts with crop models to guide adaptive strategies (Evans & Raja, 2024). Farmers can modify planting dates, select drought-resistant crops, or adjust irrigation schedules. Early warning systems reduce climate-related losses and enhance resilience. Climate change has emerged as one of the most significant threats to global agricultural stability, increasing the frequency and intensity of droughts, floods, heatwaves, and pest outbreaks. These disruptions undermine crop productivity, strain water resources, and heighten income uncertainty for farmers. Artificial Intelligence (AI) enhances climate resilience by transforming vast streams of climatic, environmental, and agronomic data into predictive and adaptive decision-support systems.

AI-driven models integrate historical weather patterns, real-time meteorological forecasts, satellite imagery, and soil sensor data to predict seasonal variability, drought probabilities, flood risks, and heat stress conditions (Evans & Raja, 2024). Such predictive capabilities enable a transition from reactive crisis management to proactive adaptation. Farmers can adjust sowing dates, select climate-resilient crop varieties, and optimize irrigation schedules based on AI-generated advisories, thereby minimizing exposure to climatic shocks. In water-scarce regions, AI-enabled irrigation systems apply water according to soil moisture status and evapotranspiration rates, reducing groundwater depletion while maintaining yields. At broader scales, AI contributes to regional drought monitoring, crop insurance risk modeling, and disaster preparedness planning, strengthening systemic resilience across agricultural value chains. By enabling adaptive responses at both farm and policy levels, AI supports climate-smart agriculture and advances progress toward climate action objectives under sustainable development frameworks.

Supply Chains and Market Intelligence

Beyond farms, AI optimizes logistics and price forecasting. Demand prediction reduces post-harvest losses, which are significant in developing economies. AI-based platforms also improve price transparency, enhancing farmer incomes and economic sustainability. While production efficiency is critical, post-harvest systems significantly influence food security outcomes. In many developing regions, inadequate logistics, poor storage infrastructure, and limited market information lead to substantial post-harvest losses, often exceeding one-quarter of total agricultural output. AI technologies enhance supply chain efficiency by analyzing transportation networks, storage conditions, and demand patterns to optimize logistics and reduce spoilage. Predictive analytics models forecast demand fluctuations and coordinate distribution schedules, improving cold-chain management and minimizing delays that degrade perishable produce. AI-based market intelligence platforms also increase price transparency by processing historical price data, weather-influenced production forecasts, trade flows, and consumption trends.

These tools enable farmers to make informed decisions regarding crop selection, harvest timing, and market entry, thereby improving bargaining power and income stability. Digital platforms powered by AI further facilitate direct connections between farmers and buyers, reducing reliance on intermediaries and lowering transaction costs. Through these mechanisms, AI strengthens economic sustainability, improves food availability, and reduces inefficiencies that previously weakened agricultural value chains.

Economic Implications

The economic impact of AI adoption in agriculture is multifaceted, influencing farm profitability, labor dynamics, and broader rural development. Precision agriculture technologies enhance yield per hectare by optimizing input use and improving crop management decisions. Simultaneously, AI-driven systems reduce costs by minimizing excess use of water, fertilizers, pesticides, and fuel. Automation through robotics and intelligent machinery further lowers labor requirements, particularly for repetitive and labor-intensive tasks, contributing to operational efficiency. In addition, improved logistics and predictive supply chain management reduce post-harvest losses, increasing the proportion of produce that reaches markets. Together, these factors generate significant long-term returns on investment, especially for medium and large farms capable of scaling technology deployment. However, high initial capital requirements, limited digital literacy, and inadequate rural connectivity constrain adoption among smallholder farmers, who represent a large share of agricultural producers in developing countries (Pandey, 2025). Without targeted policy support—such as subsidies, credit access, and training programs—AI adoption risks reinforcing existing inequalities within the agricultural sector. At the macroeconomic level, AI-enabled agriculture can enhance national food self-sufficiency, stimulate agri-tech industries, and create employment in data services, technology maintenance, and advisory sectors, underscoring its potential contribution to sustainable economic development. AI adoption can reduce labor costs and increase profitability through:

- Yield enhancement
- Input savings
- Reduced post-harvest losses

However, high capital requirements and digital skill gaps limit adoption among smallholders (Pandey, 2025).

Artificial Intelligence (AI) for Sustainable Agriculture

Sustainable agriculture seeks to balance three core objectives:

1. Productivity and profitability
2. Environmental conservation
3. Social and economic equity

The conceptual model presented here positions AI as a key enabler that supports decision-making across farm operations, supply chain management, and policy planning. AI enhances fertilizer and water use efficiency, pest and disease diagnosis, yield prediction, and risk management through advanced analytics.

AI in Agriculture: Components and Technologies

AI applications in agriculture are driven by several technological building blocks:

1. Machine Learning (ML): Algorithms that learn from data to make predictions (e.g., yield forecasting).
2. Computer Vision: Enables crop and soil monitoring via image analysis.
3. Robotics and Automation: Includes autonomous tractors and drones for spraying, weeding, and harvesting.
4. Internet of Things (IoT): Sensor networks that collect real-time data on soil moisture, temperature, and crop health.
5. Big Data Analytics: Integration of multi-source data for decision support systems.

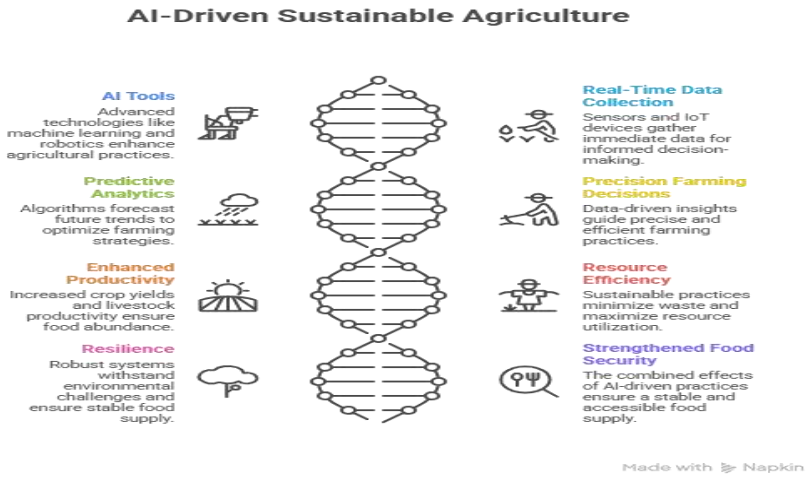


Figure 2- Artificial Intelligence (AI) driven Sustainable Agriculture

It shows Artificial Intelligence (AI) tools can drive sustainable agricultural practices, ultimately leading to strengthened food security. The framework highlights the progression from AI tool implementation and data collection to predictive analytics, precision farming decisions, and the resulting improvements in productivity, resource efficiency, and resilience.The foundation of this framework lies in the application of various AI tools, including:

1. **Machine Learning (ML):** ML algorithms can analyze vast datasets to identify patterns, predict crop yields, detect diseases, and optimize resource allocation.
2. **Computer Vision:** Computer vision enables automated monitoring of crop health, weed detection, and livestock management through image and video analysis.
3. **Internet of Things (IoT):** IoT devices, such as sensors and drones, facilitate real-time data collection on soil conditions, weather patterns, and plant growth.
4. **Robotics:** Agricultural robots can automate tasks like planting, harvesting, and weeding, reducing labor costs and improving efficiency.

Collection of real-time data -The AI tools mentioned above enable the collection of real-time data from various sources:

1. **Environmental Sensors:** These sensors monitor soil moisture, temperature, nutrient levels, and weather conditions, providing valuable insights into the growing environment.
2. **Drones and Satellites:** Aerial imagery captured by drones and satellites allows for large-scale monitoring of crop health, identifying areas of stress or disease.
3. **Agricultural Machinery:** Modern tractors and harvesters are equipped with sensors that collect data on yield, fuel consumption, and other performance metrics.
4. **Livestock Monitoring Systems:** Wearable sensors and cameras can track animal health, behavior, and location, enabling early detection of diseases and optimized feeding strategies.

AI-powered predictive analytics - The collected data is then fed into AI-powered predictive analytics systems:

1. **Yield Prediction:** ML models can predict crop yields based on historical data, weather forecasts, and soil conditions, enabling farmers to make informed decisions about planting and harvesting.
2. **Disease and Pest Detection:** AI algorithms can identify early signs of disease or pest infestations through image analysis and sensor data, allowing for timely intervention.
3. **Resource Optimization:** Predictive analytics can optimize the use of water, fertilizers, and pesticides by predicting crop needs and minimizing waste.
4. **Market Forecasting:** AI can analyze market trends and predict future demand, helping farmers make informed decisions about crop selection and pricing.

Predictive analytics- The insights generated by predictive analytics inform precision farming decisions:

1. **Variable Rate Application:** Based on real-time data and predictive models, farmers can apply fertilizers, pesticides, and water at variable rates, targeting specific areas of need and minimizing environmental impact.

2. **Optimized Irrigation:** AI-powered irrigation systems can automatically adjust watering schedules based on soil moisture levels and weather conditions, conserving water and improving crop yields.
3. **Targeted Pest Control:** Computer vision and robotics can be used to identify and remove weeds or pests with pinpoint accuracy, reducing the need for broad-spectrum pesticides.
4. **Data-Driven Planting:** AI can analyze soil conditions and weather patterns to determine the optimal planting dates and spacing for different crops.

Precision farming decisions -The implementation of precision farming decisions leads to several positive outcomes:

1. **Enhanced Productivity:** Optimized resource allocation and targeted interventions result in higher crop yields and improved livestock productivity.
2. **Resource Efficiency:** Precision farming reduces the waste of water, fertilizers, and pesticides, minimizing environmental impact and lowering input costs.
3. **Resilience:** AI-driven systems can help farmers adapt to changing climate conditions, such as droughts and extreme weather events, by optimizing resource management and diversifying crop selection.

Strengthened Food Security -The combined effects of enhanced productivity, resource efficiency, and resilience contribute to strengthened food security:

1. **Increased Food Production:** Higher crop yields and improved livestock productivity ensure a more stable and abundant food supply.
2. **Reduced Environmental Impact:** Sustainable agricultural practices minimize the environmental footprint of food production, preserving natural resources for future generations.
3. **Improved Livelihoods:** Increased productivity and reduced input costs improve the profitability of farming, enhancing the livelihoods of farmers and rural communities.
4. **Climate Change Adaptation:** AI-driven systems help farmers adapt to the challenges of climate change, ensuring a more resilient and sustainable food system.

The potential of AI to transform agriculture into a more sustainable and efficient industry. By leveraging AI tools for real-time data collection, predictive analytics, and precision farming decisions, we can enhance productivity, conserve resources, build resilience, and ultimately strengthen food security for a growing global population. Further research and development in this area are crucial to unlock the full potential of AI-driven sustainable agriculture.

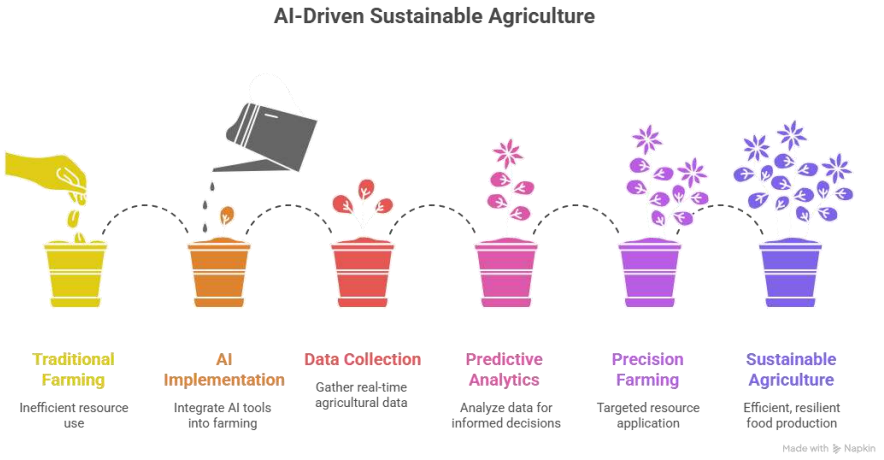


Figure 3- Conceptual Framework for AI driven Sustainable Agriculture

AI and Agricultural Productivity: Evidence and Data

AI technologies are shown to increase agricultural productivity significantly by optimizing inputs and reducing waste. Several recent studies provide empirical insights:

Yield Improvement- AI-enabled precision agriculture can lead to yield increases between 5% and 30% depending on crop type, region, and technology application. These improvements stem from optimized irrigation, fertigation, and timely pest management guided by predictive analytics.

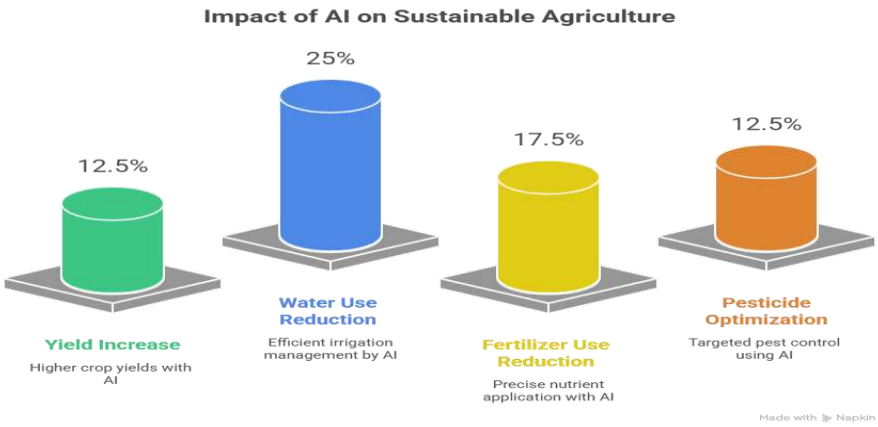


Figure 4 — Typical Impacts of AI on Agricultural Productivity

Figure 4 data reflect average performance gains across implementation contexts where precision farming technologies guide input application based on soil and crop status. Beyond direct yield improvements, these efficiencies contribute to lower production costs.

Resource Use Efficiency

AI significantly enhances resource use efficiency through optimized irrigation and nutrient management. For example, AI-driven precision irrigation models use soil moisture data and weather forecasts to trigger irrigation only when needed, reducing water use by 10–30% while maintaining yields. Precision agriculture applications have demonstrated up to 50% reduction in herbicide usage while maintaining crop productivity in controlled farm studies. Field studies integrating satellite and sensor data with ML models have also shown yield enhancement and improved soil health through targeted nutrient application, underscoring AI's potential for sustainable intensification.

Research Methodology

This study employs a systematic interdisciplinary review combined with conceptual modeling and analytical synthesis to examine the role of Artificial Intelligence (AI) in promoting sustainable agriculture, productivity enhancement, climate resilience, and food security.

The design integrates technological assessment with sustainability analysis to capture the multidimensional impacts of AI adoption in agriculture.

The research follows three stages:

1. **Systematic Evidence Collection** – Identification of peer-reviewed studies, institutional reports, and technical publications related to AI applications in agriculture.
2. **Comparative Impact Analysis** – Evaluation of reported outcomes across productivity, environmental, economic, and social dimensions.
3. **Framework Development** – Construction of an integrated conceptual model linking AI technologies with sustainability and food security outcomes.This structure allows examination of AI not merely as a technological tool but as a socio-technical system influencing agricultural transformation.

Major Applications of AI in Sustainable Agriculture

AI's versatility enables its application across the agricultural value chain—from farm planning to market access. The following subsections explore major areas where AI enhances productivity, resilience, and food security.

Precision Farming

Precision farming uses AI and IoT sensors to apply inputs—such as water, fertilizers, and pesticides—at the right place and time based on crop needs. This minimizes waste, reduces costs, and improves output quality. Precision irrigation systems driven by AI have been shown to reduce water usage by up to 30% while maintaining or improving yields In addition, soil moisture prediction models using satellite data and sequence-to-sequence neural networks help optimize irrigation schedules, reducing dependency on manual measurement.

Crop Monitoring and Disease Detection

AI-based computer vision models detect early signs of crop disease and pest infestation from drone and satellite imagery, enabling early intervention.

These tools can identify patterns invisible to the naked eye, helping farmers reduce crop loss and pesticide misuse. For example, deep learning models now perform yield prediction, pest and disease diagnosis, and soil fertility mapping with high accuracy, significantly enhancing operational decision-making in farming.

Climate Resilience and Risk Management

Climate variability presents a major risk to agriculture, impacting crop yields, water resources, and livestock health. AI predictive models analyze climate data and provide early warnings, enabling farmers to adjust sowing dates, select resilient crop varieties, and anticipate irrigation needs—thereby mitigating climate risks. In many regions, AI tools improve resilience by incorporating multi-source climate forecasts into farming decisions, a critical function as unpredictable weather events become more frequent.

Supply Chain and Market Access

AI also optimizes supply chain logistics and market pricing through advanced analytics. Improved demand forecasting, logistics routing, and price transparency help reduce post-harvest losses—which can account for nearly 30% of production in developing countries—thereby strengthening food security. AI-based platforms provide real-time market intelligence to farmers, enabling better negotiation of prices and access to profitable markets, which enhances economic sustainability.

Economic Implications for Farmers

Cost–Benefit Advantages

While initial investments in AI technologies are often high, long-term economic benefits are substantial. These include:

1. Reduced input costs (water, fertilizer, pesticides)
2. Increased yields and profitability
3. Lower labor costs through automation (10–20%)
4. Diversified income opportunities through data services and agri-analytics

Small case studies (e.g., Kenyan smallholders using Virtual Agronomist AI tools) reflect how personalized AI advisories improved yields significantly compared to traditional practices.

Barriers to Adoption

Despite economic benefits, barriers include:

1. High upfront costs
2. Limited digital infrastructure
3. Technical skill gaps
4. Data privacy and algorithmic bias concerns

Smallholder farmers often lack access to credit and connectivity required for adopting sophisticated AI systems, limiting equitable benefits.

1. CASE STUDIES: GLOBAL AND REGIONAL INSIGHTS

Kenya: AI Advisory Tools

In Kenya, tools like Virtual Agronomist and Plant Village use AI to provide crop-specific advice to farmers, helping them optimize fertilization and pest management. Farmers adopting these tools witnessed increases in yields—e.g., coffee yield rising from 2.3 to over 7 tons per hectare following AI guidance.

India: Drone-Based Precision Agriculture

A study in Karnataka demonstrated that drone technology reduced water consumption for agrochemical spraying by up to 90% and improved yields for crops like finger millet and pigeon pea by 5–10%. Additionally, Punjab Agricultural University developed IoT and AI-based irrigation systems that reduced water use in rice-wheat cycles by 23.3%, contributing to food security and sustainability in India's grain belt.

*Environmental and Social Impac*ts

Environmental Sustainability

AI enhances environmental outcomes by:

1. Reducing water and chemical use
2. Minimizing nutrient runoff and greenhouse gas emissions

3. Promoting biodiversity through targeted pest control

By optimizing resource inputs, AI contributes to environmental sustainability without compromising productivity.

Social Equity

While AI holds promise, there is a risk of increasing digital divides. Farmers with limited access to technology and training may be left behind. Inclusive policies and extension services are vital to ensure equitable access to AI benefits.

2. DISCUSSION: AI IN AGRICULTURE AND LINKAGES WITH SUSTAINABLE DEVELOPMENT GOALS (SDGS)

The integration of Artificial Intelligence (AI) into agricultural systems represents more than technological modernization; it constitutes a structural shift toward data-driven, climate-smart, and resource-efficient food production. The evidence presented across productivity, resilience, supply chains, and economic performance demonstrates that AI operates as a cross-cutting enabler of sustainable development. Its impacts extend across multiple Sustainable Development Goals (SDGs), reinforcing the interdependence between food systems, environmental sustainability, and socioeconomic development.

AI's contribution to SDG 2 (Zero Hunger) is evident in its capacity to enhance crop yields, reduce losses, and stabilize food production under climate stress. Precision farming techniques improve input efficiency and crop monitoring, resulting in higher productivity without proportional increases in land use. Moreover, AI-driven early warning systems mitigate climate-related yield variability, strengthening food supply stability. By reducing post-harvest losses through optimized logistics and storage management, AI also increases the effective availability of food, a critical dimension of food security beyond mere production.

In relation to SDG 12 (Responsible Consumption and Production), AI supports sustainable resource management by reducing waste in water, fertilizers, and agrochemicals. Predictive models ensure that inputs are applied only where and when needed, minimizing environmental externalities such as nutrient runoff and soil degradation.

AI-enabled supply chain analytics further reduce inefficiencies that lead to spoilage and overproduction. These mechanisms collectively advance more sustainable production-consumption patterns across agricultural value chains.

AI also plays a central role in SDG 13 (Climate Action)**.** Climate-smart decision-support systems help farmers adapt to changing weather patterns, reducing vulnerability to extreme events. Predictive climate analytics guide adaptive cropping strategies, irrigation planning, and risk mitigation, transforming agriculture into a more resilient system. At the policy level, AI-generated climate risk maps assist governments in disaster preparedness and resource allocation, reinforcing national adaptation strategies.

Beyond environmental goals, AI adoption influences SDG 8 (Decent Work and Economic Growth) and SDG 9 (Industry, Innovation, and Infrastructure) by stimulating agri-tech innovation ecosystems and creating employment in digital advisory services, data analytics, and equipment maintenance. However, these gains depend on inclusive infrastructure development; without equitable access, AI could widen the digital divide, contradicting the equity principles underpinning sustainable development.

Overall, AI-enabled agriculture exemplifies how technological innovation can support an integrated SDG framework. Yet, its effectiveness depends on governance structures that ensure equitable access, ethical data use, and institutional capacity building.

Environmental Sustainability Impacts of AI in Agriculture

Environmental sustainability is a core pillar of sustainable agriculture, and AI contributes significantly to reducing the ecological footprint of food production. Traditional agricultural intensification has often relied on increased use of water, fertilizers, and pesticides, leading to soil degradation, water pollution, and greenhouse gas emissions. AI-driven precision agriculture alters this trajectory by enabling sustainable intensification, where output growth is decoupled from resource overuse.One of the most significant environmental benefits of AI lies in water conservation. Smart irrigation systems use soil moisture sensors, evapotranspiration models, and weather forecasts to deliver water precisely when crops require it.

This targeted application reduces water wastage and groundwater depletion, particularly in arid and semi-arid regions where water scarcity threatens agricultural viability. Efficient irrigation also lowers energy use associated with water pumping, indirectly reducing carbon emissions.

AI also enhances nutrient management. Machine learning models analyze soil nutrient data and crop growth stages to guide variable-rate fertilizer application. This approach prevents excessive fertilizer use, reducing nitrogen runoff into water bodies and mitigating eutrophication. Improved nutrient efficiency also lowers nitrous oxide emissions, a potent greenhouse gas associated with agricultural soils.In pest and weed management, computer vision and robotics enable targeted interventions. AI-guided sprayers and robotic weeders identify specific areas of infestation, minimizing blanket pesticide applications. This precision reduces chemical residues in soil and water, protects beneficial insects, and supports biodiversity conservation. Such approaches contribute to ecological balance while maintaining crop health.

AI further supports soil health monitoring by analyzing satellite imagery and sensor data to detect early signs of degradation, salinity, or erosion. Timely interventions such as crop rotation, cover cropping, or organic amendments can then be implemented to restore soil quality. Healthy soils improve carbon sequestration potential, linking AI-enabled agriculture with climate mitigation efforts.At a broader scale, AI-driven land-use analytics help policymakers balance agricultural expansion with ecosystem conservation. By identifying high-productivity zones and monitoring deforestation risks, AI contributes to sustainable land management strategies that protect natural habitats.Despite these environmental benefits, potential risks exist. Increased reliance on digital technologies may lead to energy consumption associated with data processing and equipment manufacturing. Therefore, sustainable AI deployment must consider life-cycle environmental costs alongside agricultural gains.In sum, AI enhances environmental sustainability by optimizing resource use, reducing pollution, supporting biodiversity, and promoting climate mitigation. When embedded within supportive governance frameworks, AI can help transition agriculture toward a more ecologically balanced and resilient system.

Challenges and Ethical Considerations

Despite widespread opportunities, several challenges pose constraints:

1. Algorithmic bias leading to unequal advice across regions and soil types
2. Data privacy and ownership issues in agricultural data ecosystems
3. Infrastructure gaps in rural connectivity
4. Skilled workforce shortages for technology adoption and maintenance.Ethical frameworks must be developed to govern AI use in agriculture, ensuring transparency, fairness, and accountability in data use and recommendations.

Policy Framework and Recommendations

To mainstream AI for sustainable agriculture, policymakers should consider:

1. Investing in rural digital infrastructure
2. Providing financial support and subsidies for AI adoption
3. Strengthening public–private partnerships
4. Developing data governance and farmer protection policies
5. Promoting capacity building and digital literacy programs

Such holistic policy frameworks will enable inclusive and sustainable technology adoption.

CONCLUSION

AI has immense potential to transform agriculture into a sustainable, productive, and resilient system capable of meeting future food security challenges. By enhancing productivity, optimizing resources, and improving decision-making, AI provides a pathway toward achieving global development goals. However, challenges related to cost, infrastructure, equity, and ethics must be addressed through comprehensive policy and institutional support. With the right frameworks, AI can help create a balanced agricultural system that supports livelihoods, conserves the environment, and sustains global food supplies.AI represents a transformative force in sustainable agriculture. By enhancing productivity, conserving resources, and improving resilience, AI supports global food security.

However, equitable adoption depends on inclusive policies, infrastructure, and ethical governance. When aligned with sustainability principles, AI can help create resilient agricultural systems capable of feeding future generations.

REFERENCES

Barbedo, J. G. A. (2025). A review of artificial intelligence techniques for wheat crop monitoring and management. Agronomy, 15(5), 1157. https://doi.org/10.3390/agronomy15051157

Barbedo, J. G. A. (2025). A review of artificial intelligence techniques for wheat crop monitoring and management. *Agronomy, 15*(5), 1157. https://doi.org/10.3390/agronomy15051157

Efremova, N., Zausaev, D., & Antipov, G. (2019). Prediction of soil moisture content using satellite data and AI networks.

Efremova, N., Zausaev, D., & Antipov, G. (2019). Prediction of soil moisture content using satellite data and AI networks.

Evans, R., & Raja, S. (2024). AI-based frameworks for sustainable farming. International Journal of Environmental Sciences. The ASPD

Evans, R., & Raja, S. (2024). AI-based frameworks for sustainable farming. *International Journal of Environmental Sciences.*

Food and Agriculture Organization. (2022). The future of food and agriculture: Drivers and triggers for transformation. FAO.

Food and Agriculture Organization. (2022). *The future of food and agriculture: Drivers and triggers for transformation.* FAO.

Hasan, M. M., Islam, M. U., & Sadeq, M. J. (2022). Technological adaptation of advanced farming through AI, IoT, and robotics. arXiv

Hasan, M. M., Islam, M. U., & Sadeq, M. J. (2022). Technological adaptation of advanced farming through AI, IoT, and robotics. *arXiv.*

International Journal for Multidisciplinary Research. (2025). Benefits of AI in agricultural transformation. Jescae.

Pandey, A. (2025). Artificial intelligence as a revolution in agriculture for ensuring food security and sustainability: A review. International Journal of Research in Agronomy, 8(3S), 309–312. https://doi.org/10.33545/2618060X.2025.v8.i3Sd.2741

Pandey, A. (2025). Artificial intelligence as a revolution in agriculture for ensuring food security and sustainability: A review. *International Journal of Research in Agronomy, 8*(3S), 309–312.

SpringerLink. (2025). AI and data analytics in precision agriculture for sustainable development. Springer Link

Srikanthnaik, J. (2024). Artificial Intelligence and Machine Learning for Precision in Agriculture: A Comprehensive Systematic Review. International Journal of Agriculture and Environmental Sciences, 7(6), 762–767. https://doi.org/10.33545/2618060X.2024.v7.i6j.2794

Srikanthnaik, J. (2024). Artificial intelligence and machine learning for precision in agriculture: A comprehensive systematic review. *International Journal of Agriculture and Environmental Sciences, 7*(6), 762–767.

Sustainability Directory. (2025). Impact of AI on crop yields and resource efficiency. Sustainability Directory

Sustainability Directory. (2025). What statistics indicate the impact of AI on sustainable agriculture? Sustainability Directory

CHAPTER 4
SENSITIVITY ANALYSIS OF BOVINE MASTITIS DISEASE: A MATHEMATICAL MODELLING APPROACH

[1]O.A. ODEBİYİ
[2]J. K. OLADEJO
[3]M.O. ADEYEMİ
[4]E.O. ELİJAH

[1]Department of Mathematics, University of Ilesa, Ilesa, Osun State, Nigeria, oaodebiyi@lautech.edu.ng, 0009-0007-8173-6755
[2]Department of Mathematics, University of Ilesa, Ilesa, Osun State, Nigeria
[3]Department of Mathematics, Federal University of Technology, Minna, Niger State
[4]3Department of Mathematics, Federal University of Technology, Minna, Niger State

INTRODUCTION

Bovine mastitis is an inflammation of the udder and remains one of the most challenging veterinary diseases to control. It is defined as an inflammatory response of the mammary gland tissue, typically resulting from physical trauma or infection by microorganisms. Mastitis is recognized as the most prevalent disease causing significant economic losses in the dairy industry, primarily due to reduced milk yield and deterioration in milk quality [1].

The condition is characterized by a persistent inflammatory reaction of the udder tissue, triggered either by mechanical injury or microbial infection, and is widely regarded as the leading cause of financial loss in dairy production [1],[2],[4],[5]. Based on the degree of inflammation, bovine mastitis can be classified into three forms: clinical, subclinical, and chronic.

Clinical mastitis is readily identifiable through visible abnormalities such as swelling, redness of the udder, and fever in affected cattle. It is most often associated with bacterial infection, which induces inflammation, pain, discomfort, reduced milk production, and diminished milk quality, with potential spread to other quarters or animals. The primary causative microorganisms are grouped into two categories: environmental bacteria, including *Streptococcus uberis* and *Streptococcus dysgalactiae*, and contagious bacteria, such as *Staphylococcus aureus* and *Mycoplasma* spp. [3],[12],[14].

Mastitis develops when bacteria, often originating from the infant's mouth, enter a breast duct through a crack in the nipple. The affected quarter typically becomes tender to touch and causes pain to the animal. If acute mastitis is left untreated and the inflammatory process persists, it may progress to chronic mastitis, resulting in irreversible damage to the milk-secreting tissue and permanent loss of milk production. Such pathological changes are generally incurable and lasting [6].

Most likely, other causes of infection include chronic Mastitis and a rare form of cancer called inflammatory carcinoma. Hormonal changes in the body can cause the milk ducts to become clogged with dead skin cells and debris. These clogged ducts make the breast more open to bacterial infection and the infection can still reoccur even after the treatment with antibiotics. Other symptoms of Mastitis are Fatigue, breast enlargement, tenderness and swelling, fever and chills, Abscess, and persistent fever.

The primary source of environmental Mastitis pathogens is the habitat of the cow, streptococcus species and Gram-negative bacteria (*Escherichia coli* and *klebsiella*) are examples included in this group. Other main symptoms are lack of appetite, hindrances in mobility due to swollen udder and pain. The swollen mammary gland is some time hot and the mere touching can cause pain and discomfort to the animals.

Mastitis can be transmitted by direct contact between an infected and a susceptible animal which becomes infected by inhaling droplets disseminated in the environment. It can also be transmitted through an infected vector such as horn fly and possibly housefly [8-10,12]. Clinical researches also showed the transmission through flies to cattle and cattle-cattle. The animal suffering from this disease may however recover spontaneously but usually drug administration is necessary to maintain productivity and this can be achieved through systemic and intra-mammary administration of antibiotics, supportive fluid and anti-inflammatory therapy [4,6,12].

Various mathematical models have been developed to design strategies for controlling disease outbreaks, allowing trade-offs in selecting the most effective treatment options. The basic reproduction number

serves as a critical threshold parameter, enabling medical and public health practitioners to determine whether an infection will eventually fade out within a population [15]. The incidence rate is a crucial metric in understanding disease epidemiology, revealing transmission dynamics, and informing control strategies [16],[20].

This study explores a mathematical modelling approach to analyse the sensitivity of an in-vitro bovine mastitis disease model, incorporating non-linear incidence and treatment functions.

The paper is organized as follows. In section 2, we formulate and explain the model and the existence and uniqueness of the model was shown. The basic reproduction number and the sensitivity analysis was carried out in order to know which of the parameter is most sensitive and its implications to the basic reproduction number in section 3. Section 4 gives the numerical simulations while section 5 submit the concluding remark of the study.

1. FORMULATION AND PROPERTIES OF THE MASTITIS MODEL

1.1. Mathematical Formulation

In this model, the cattle population is subdivided into the subpopulations of six classes consisting of Susceptible class $E(t)$, Subclinical infective class $A(t)$, Clinical infective class $I(t)$, Chronic infective class $C(t)$, and the Recovered Class $R(t)$. The total population of cattle at any time, *t*, is:

An SIR model with saturated incidence rate $\left(\frac{\beta_1 A}{1+\alpha_1 A}+\frac{\beta_2 I}{1+\alpha_2 I_1}\right)$ is explored. Susceptible cattle come into effective contact with infectious individuals at the subclinical and clinical infective class and thereafter progresses from the exposed class to the subclinical class at a rate (ρ).

and a fraction of them moved to the clinical class. Some cattle died naturally while at exposed class, subclinical class and at every other infective classes. While at subclinical infective class, some cattle develop into clinical infective class at a rate (σ) and some progresses to chronic class at a rate (θ). Also while still receiving treatment at clinical class, some progresses to chronic class due to delay in treatment or failed treatment while some moves to recovered class at a rate (γ).

The interactions between the cattle-cattle transmission is thereby depicted by the schematic diagram in Figure 1.

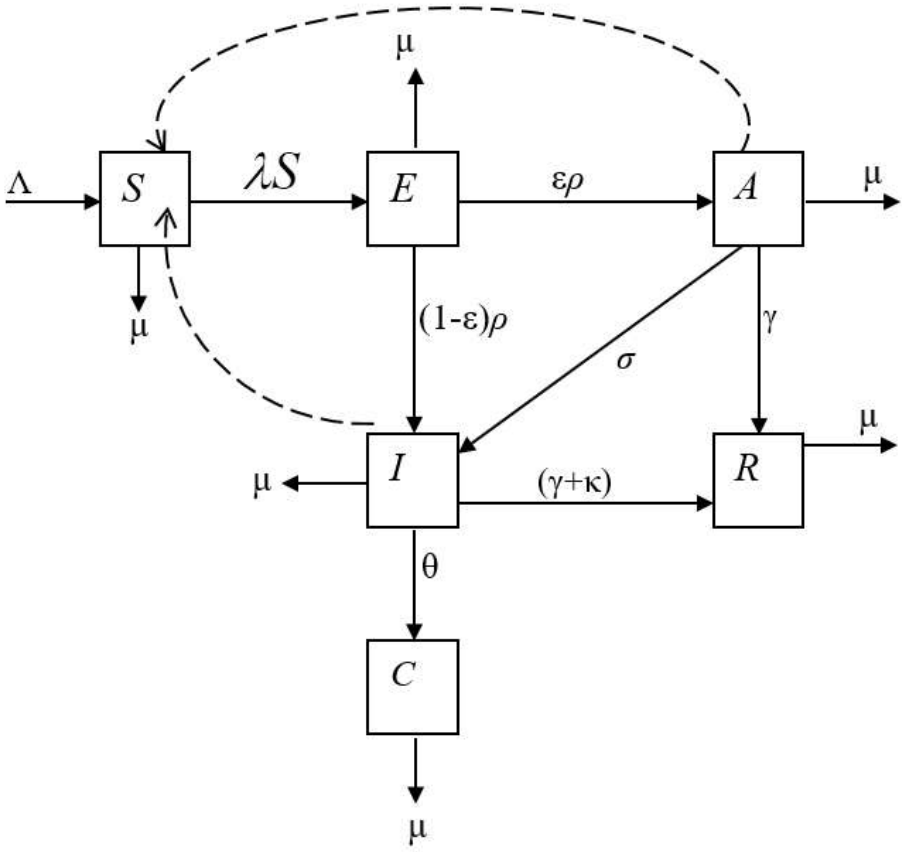


***Figure* 1:** *The Mastitis Model's Schematic Diagram*

A system of ordinary differential equations, using the saturated incidence rate and non-linear treatment function, is formulated as below:

$$\left.\begin{aligned}
\frac{dS}{dt} &= \Lambda - \left(\frac{\beta_1 A}{1+\alpha_1 A} + \frac{\beta_2 I}{1+\alpha_2 I}\right) S - \mu S \\
\frac{dE}{dt} &= \left(\frac{\beta_1 A}{1+\alpha_1 A} + \frac{\beta_2 I}{1+\alpha_2 I}\right) S - (\mu + \rho) E \\
\frac{dA}{dt} &= \varepsilon\rho E - (\mu + \sigma + \gamma) A \\
\frac{dI}{dt} &= (1-\varepsilon)\rho E + \sigma A - \left(\mu + \theta + \gamma + \frac{a\tau}{1+b\tau I}\right) I \\
\frac{dC}{dt} &= \theta I - (\mu + \delta + d) C \\
\frac{dR}{dt} &= \gamma A + \left(\gamma + \frac{a\tau}{1+b\tau I}\right) I - \mu R;
\end{aligned}\right\} \quad (1)$$

subject to the initial conditions:

$$S(0) \geq 0; E(0) \geq 0; A(0) \geq 0; I(0) \geq 0, C(0) \geq 0; R(0) \geq 0$$

.

The parameters of the model are described in the Table 1.

Table 1: Model's Parameters and description

Parameters	Description	Value (day^{-1})	Source
Λ	Per capital recruitment rate	$\frac{1}{5\times 365}$	[8]
β_1	Transmission rates for subclinical infectious cattle	0.00230	[12]
β_2	Transmission rates for clinical infectious cattle	0.00235	Assumed
α_1	Inhibition coefficient for $A(t)$	1.005	[12]
α_2	Inhibition coefficient for $I(t)$	1.015	Assumed
ρ	Progression rate from Exposed class	$\frac{1}{6\times 7}$	[8]
σ	Rate of developing clinical symptoms	1.005	[12]

θ	Rate of developing into chronic stage	0.010	[12]
μ	Per capital natural mortality	$\frac{1}{5\times 365}$	[8]
δ	Mastitis induced death rate	0.005	[8]
ε	Proportion of exposed cattle that develop subclinical cases	0.333	[12]
γ	Natural recovery rate	0.015	[12]
τ	Maximum rate of treatment	$\frac{1}{28}$	[8]
a	Rate of cure of the treatment	6.5	[21]
b	Rate of delay in treatment	5.0	[21]
d	Rate of curling of chronic infective cattle	0.0025	[12]

Table 2: Model Variables

Variables	**Description**
$S(t)$	Susceptible class
$E(t)$	Exposed class
$A(t)$	Subclinical infective class
$I(t)$	Clinical infective class
$C(t)$	Chronic infective class
$R(t)$	Recovered Class

1.2. Positivity and Boundedness of Solutions of the Model

We can show from model (1) that the state variables are non-negative and the solutions remain positive for all time $t \geq 0$. Here, the parameters in the model are assumed to be positive.

Theorem 1: Let the initial conditions or values of the state variables be such that

$$\{(S(0) \geq 0, E(0) \geq 0, A(0) \geq 0, I(0) \geq 0, C(0) \geq 0, R(0) \geq 0) \in \Omega\}$$

, then the set

$$\{S(t), E(t), A(t), I(t), C(t), R(t)\}$$

is non-negative in Ω for all time $t \geq 0$.

Proof: Considering the first equation in (1) are considered for the positivity of the state variables as follows;

Using the approach of [7, 12]

$$\frac{dS}{dt} \geq -(\lambda + \mu)S$$

$$\int \frac{1}{S} dS \geq -\int (\lambda + \mu) dt$$

$$S(t) \geq S_0 e^{-(\lambda+\mu)t} \geq 0$$

Hence, $S(t) \geq 0$

(2)

It is possible to show using the same procedure for other state variables that:

$$E(t) \geq E(0)e^{-(\theta+\mu+\sigma)t} \geq 0, A(t) \geq A(0)e^{-(\mu+\varepsilon)t} \geq 0, I(t) \geq I(0)e^{-(\mu+\gamma+d)t} \geq 0,$$
$$C(t) \geq C(0)e^{-(\sigma+\mu)t} \geq 0, R(t) \geq R(0)e^{-(\mu+d)t} \geq 0$$

This shows that all the solutions of equation (1) are positive for all $t \geq 0$. Therefore, the Bovine mastitis transmission model stated in (1) is both epidemiologically significant and numerically well posed in an attainable given region $\Omega \geq 0$.

Theorem 2: Every solution in the region

$$\Omega = \left\{ \left(S(t), E(t), I(t), A(t), C(t), R(t) \in \Omega_+^6 : N(t) \leq \frac{\Lambda}{\mu} \right) \right\}$$

is positively invariant with respect to mastitis model (1) in cattle populations. The solutions for the system are contained and remain in the region Ω for all time $t \geq 0$.

Proof: Considering the equation of the model, and adding up all the derivatives with respect to time t, we obtained

$$\frac{dN(t)}{dt} = \Lambda + \mu(S + E + A + I + C + R) + (\mu + \delta + d)C + \mu R$$

$$\frac{dN(t)}{dt} = \Lambda + \mu N$$

$$N \le \frac{\Lambda}{\mu} + \left(N_0 - \frac{\pi}{\mu}\right)e^{-\mu t}$$

where N_0 is the initial size of the population

Therefore,

$$\lim_{t\to\infty} N(t) \le \frac{\Lambda}{\mu}$$

This result implies that HIV/AIDS model (1) has non-zero negative and bounded solution in the region Ω, and all the solutions starting in Ω approach, enter or stay in Ω. Hence, it is sufficient to conclude that the model is epidemiologically well posed.

2. MATHEMATICAL ANALYSIS OF THE MODEL

2.1 Mastitis-free Equilibrium

In the absence of mastitis,

$$S(t) \neq 0, E(t) = A(t) = I(t) = C(t) = R(t) = 0$$

, then the cattle populations are in a state of mastitis-free equilibrium, E_0, obtained by solving the model equations (1) subject to

$$\frac{dS}{dt} = 0,\ \frac{dE}{dt} = 0,\ \frac{dA}{dt} = 0,\ \frac{dI}{dt} = 0,\ \frac{dC}{dt} = 0,\ \frac{dR}{dt} = 0.$$

The mastitis free equilibrium is obtained as

$$E_0 = \left(\frac{\Lambda}{\mu}, 0, 0, 0, 0, 0\right) \quad (3)$$

2.2 Reproduction Number R_0

The computation of the basic reproduction number is essential. The basic reproduction number R_0 is defined as the effective number of secondary infections caused by infected individual during his entire period of infectiousness [17]. This definition is given for the model that represents the spread of infection in a population. In compartmental models for infectious diseases transmission, individuals are classified into different sub-classes while the others are the non-disease compartment. Thus, a general compartmental disease transmission model can be written in terms of F_i representing new infections rate in the ith disease compartment and the V_i stands for the transition terms.

Using the next generation matrix approach described by [11,13], the basic reproduction number is defined as the spectral radius of FV^{-1} [30], that is, $R_0 = \rho\left(FV^{-1}\right),$

where,

$$F = \begin{bmatrix} 0 & \frac{\beta_1 \Lambda}{\mu} & \frac{\beta_2 \Lambda}{\mu} & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \text{ and}$$

$$V = \begin{bmatrix} G_1 & 0 & 0 & 0 \\ -\varepsilon\rho & G_2 & 0 & 0 \\ -(1-\varepsilon)\rho & -\sigma & G_3 + a\tau & 0 \\ 0 & 0 & -\theta & G_4 \end{bmatrix} \quad (4)$$

with

$$K_1 = \mu + \rho, K_2 = \mu + \sigma + \gamma, K_3 = \mu + \theta + \gamma, K_4 = \mu + \delta + d, \quad (5)$$

$$V^{-1}=\frac{1}{K_1K_2\left(K_3+a\tau\right)}\begin{bmatrix} K_2\left(K_3+a\tau\right)K_4 & 0 & 0 & 0 \\ \varepsilon\rho\left(K_3+a\tau\right)K_4 & K_1\left(K_3+a\tau\right)K_4 & 0 & 0 \\ \varepsilon\rho\sigma K_4+K_2(1-\varepsilon)K_4 & \sigma K_1K_4 & K_1K_2K_4 & 0 \\ \varepsilon\rho\sigma\theta+(1-\varepsilon)\rho\theta K_2 & K_1\sigma\theta & K_1K_2\theta & K_1K_2\left(K_3+a\tau\right) \end{bmatrix} \quad (6)$$

The next generation matrix, G, is $G=FV^{-1}$,

$$FV^{-1}=\begin{pmatrix} \frac{\beta_1\varepsilon\rho S}{K_1K_2}+\frac{\beta_2S\left(\varepsilon\rho\sigma+(1-\varepsilon)\rho K_2\right)}{K_1K_2(K_3+a\tau)} & \frac{\beta_1S}{K_2} & \frac{\beta_1S\sigma}{K_2(K_3+a\tau)} & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad (7)$$

Therefore, the effective reproduction number is the leading eigenvalue of the matrix FV^{-1}, computed as the dominant eigenvalue of G obtained by the characteristic equation of FV^{-1}, and the dominant eigenvalue is the basic reproduction number for mastitis. That is,

$$\lambda=\begin{vmatrix} 0 \\ 0 \\ 0 \\ \frac{\Lambda\rho\left(a\varepsilon\tau\beta_1+\varepsilon\sigma\beta_2-\varepsilon K_2\beta_2+\varepsilon K_3\beta_1+K_2\beta_2\right)}{\mu K_1K_2\left(a\tau+K_3\right)} \end{vmatrix} \quad (8)$$

Hence,

$$R_0=\frac{\Lambda\rho\left(a\varepsilon\tau\beta_1+\varepsilon\sigma\beta_2-\varepsilon K_2\beta_2+\varepsilon K_3\beta_1+K_2\beta_2\right)}{\mu K_1K_2\left(a\tau+K_3\right)} \quad (9)$$

2.3 Sensitivity Analysis of the Reproduction Number

Theoretical methods are sufficiently advanced so that it is intellectually dishonest to perform modelling without sensitivity analysis. Following [18], we used the normalized forward sensitivity index also called elasticity as it is the backbone of nearly all sensitivity analysis techniques and are computationally efficient. Sensitivity analysis can as well help the reviewer to determine which parameters are the key drivers of a model's results.

Furthermore, as the basic reproduction number, R_0 is a measure of the potential for the disease spread in a population, we computed the sensitivity index of the basic reproduction number, R_0 with respect to a parameter value, P given by: $S_p^{R_0} = \frac{\partial R_0}{\partial P} * \frac{P}{R_0}.$ We therefore evaluate the sensitivity indices at the baseline parameter values given.

In determining how best to reduce human mortality and morbidity due to AIDS, the sensitivity indices of the effective reproduction number R_0 to the parameters in the model was calculated following the approach of [12],[18],[19]. These indices tell us how crucial each parameter is to disease transmission and prevalence and discover parameters that have a high impact on R_0 and should be targeted by intervention strategies.

Sensitivity analysis allow us to measure the relative change in a state variable when a parameter change. The normalized forward sensitivity index of a variable to a parameter is a ratio of the relative change in the variable to the relative change in the parameter. When a variable is differentiable function of the parameter, the sensitivity index may be alternatively defined using partial derivatives.

Now, it is already shown that the explicit expression of R_0 is given by

$$R_0 = \frac{\Lambda\rho(a\varepsilon\tau\beta_1 + \varepsilon\sigma\beta_2 - \varepsilon K_2\beta_2 + \varepsilon K_3\beta_1 + K_2\beta_2)}{\mu K_1 K_2 (a\tau + K_3)} \quad (10)$$

The normalized forward sensitivity indices of R_0 with respect to its parameters are given in the Table 3 below.

Table 3: Sensitivity Indices of R_0 in terms of the Model's parameter baseline values

Variables	Baseline Value	Sensitivity Index
Λ	$\frac{1}{5\times 365}$	1.000 00
β_1	0.002300	0.076 39498 901
β_2	0.002315	0.923 60501 16
a	1.005	-0.832 03709 28
ε	0.333	0.005 56151 1740
ρ	$\frac{1}{6\times 7}$	0.025 83486 012
σ	1.005	-0.070 59332 307

θ		0.010	0.035841597 88
μ	$\frac{1}{5\times 365}$		0.025834860 12
γ		0.015	0.025834860 12
τ	$\frac{1}{28}$		-0.832037092 9

Variables	Baseline Value	Sensitivity Index
		1.00000
	0.002300	0.07639498901
	0.002315	0.92360501 16
	1.005	-0.832037092 8
	0.333	0.00556151174 0
		0.02583486012

1.005 -0.07059332307
0.010 0.03584159788
0.02583486012
0.015 0.02583486012
-0.83203 70929

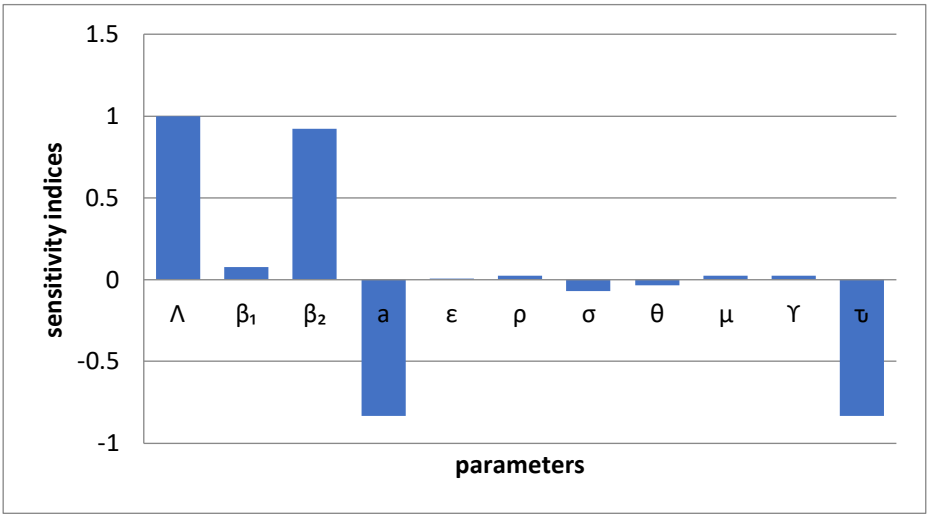


Figure 2: Graphical Representation of the Sensitivity Indices of R_0

Sensitivity analysis is a method used to determine how different input parameters affect the output of a model. It helps identify which parameters have the most impact on the model's predictions or outcomes. It identifies key parameters that need precise estimation or control and equally helps uncertainty in model predictions and guides interventions or control strategies by highlighting influential factors.

From figure 2, the most sensitive parameter is Per capital recruitment rate (Λ). Other parameters such as the transmission rate for clinical infectious cattle (β_2), Transmission rate for sub-clinical infectious cattle (β_1), Maximum rate of treatment (γ), among others are also sensitive to mastitis reproduction number, R_0. The implication of these is that. in $P_{\Lambda}^{R_0} = 1.0000$ implies that increasing or (decreasing) Λ by 10% increases (or decreases) R_0 by 10%, while $P_{\beta_2}^{R_0} = \mathbf{0.9236050116}$ means that increasing or (decreasing) (β_2) by 100% decreases or (increases) R_0 by 92.36050116%. Again, $P_{\theta}^{R_0} = 0.03584159788$ means that increasing or (decreasing) (θ) by 10% decreases or (increases) R_0 by 3.584159788%. Also, $P_{\tau}^{R_0} = 0.8320370929$ imply that increasing or (decreasing) maximum rate of treatment (τ) by 100% increases or (decreases) R_0 by 83.20370929%. Also, $P_{\sigma}^{R_0} = 0.07059332307$ means that increasing or (decreasing) (σ) by 10% decreases or (increases) R_0 by 0.7059332307%

3. NUMERICAL SIMULATIONS AND DISCUSSION OF RESULTS

3.1 Simulations and Results

The simulation was performed to examine the sensitivity of the basic reproduction number (R_0) to variations in key epidemiological parameters. The outcomes are presented in the form of 3D contour diagrams, which illustrate how changes in parameter values influence the dynamics of the susceptible, exposed, subclinical infective, clinical infective, chronic, and recovered populations. This sensitivity analysis, based on a set of reasonable parameter values, provides insight into the relative impact of each parameter on the numerical spread and progression of mastitis within the modelled population.

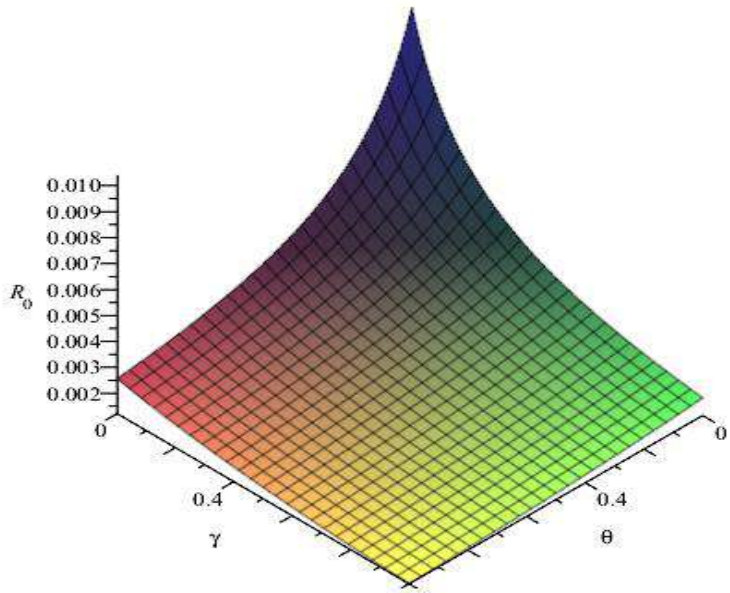


Fig 4.1: Sensitivity of the basic reproduction number to the parameters γ *and* θ

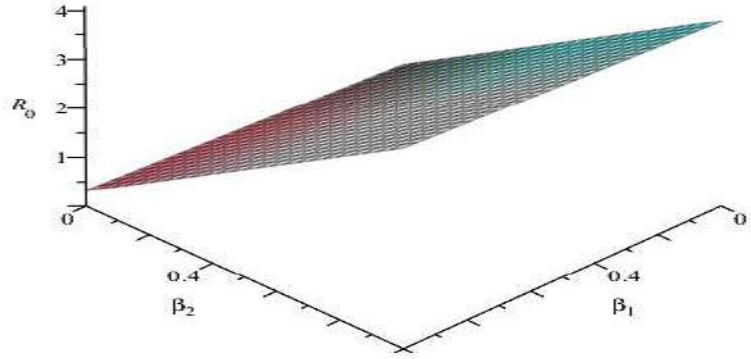


Fig 4.2: Sensitivity of the basic reproduction number to the parameters β_2 *and* β_1

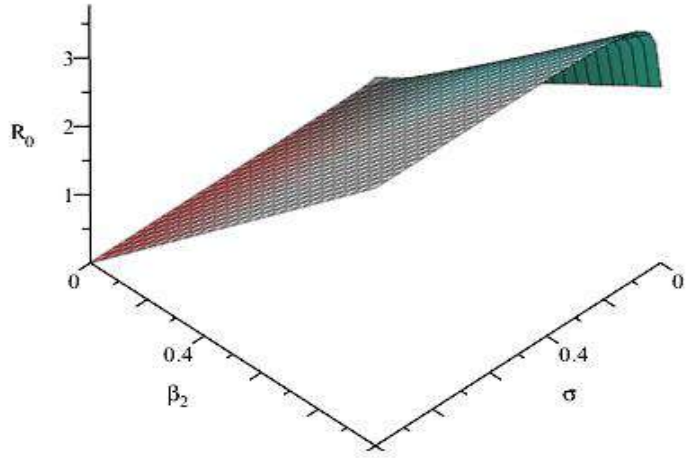


Fig 4.3: Sensitivity of the basic reproduction number to the parameters β_2 *and* σ

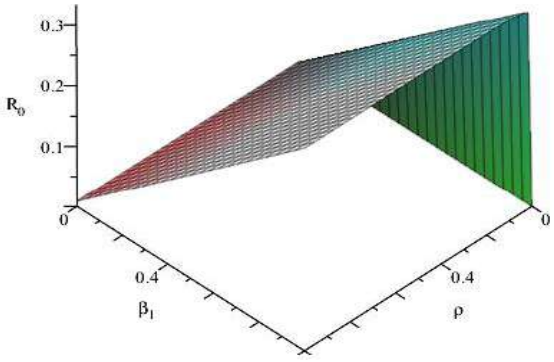


Fig 4.4: Sensitivity of the basic reproduction number to the parameters β_1 *and* ρ

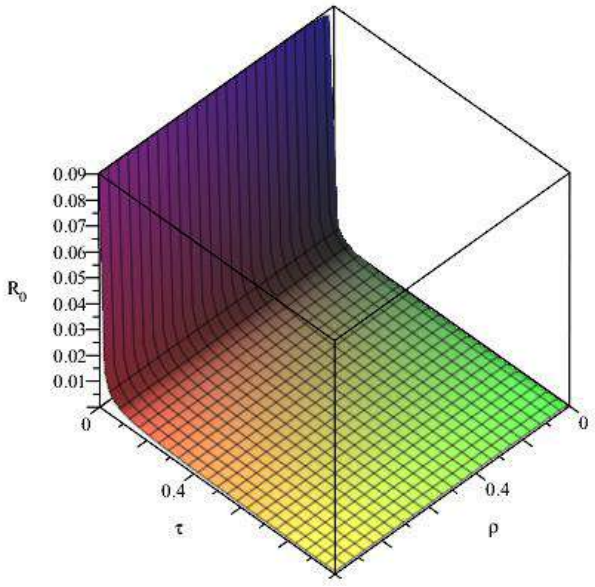


Fig 4.5: Sensitivity of the basic reproduction number to the parameters τ *and* ρ

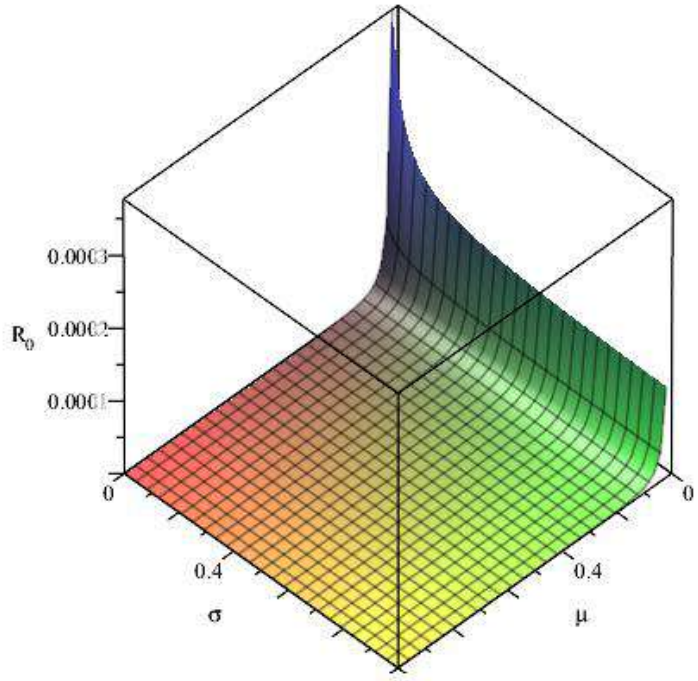


Fig 4.6: Sensitivity of the basic reproduction number to the parameters σ *and* μ

3.2 Discussion of results

Figure 4.1 illustrates the relationship between natural recovery rate (γ) and Rate of developing into chronic stage (θ) on the basic reproduction number. Notably, as the natural recovery rate increases, the basic reproduction number rises. Also, increasing (θ) leads to an increase in the basic reproduction number. Fig 4.2 demonstrates that as the transmission rate for subclinical infectious cattle increases (β_1), the basic reproduction increases and likewise, an increase in transmission rate for clinical infectious cattle (β_2), leads to increase in the basic reproduction number.

Figure 4.3 also shows the plot of Sensitivity of the basic reproduction number to the parameters (γ) and (σ). It shows that increase in the value of (β_2) led to a corresponding increase in the basic reproduction number and conversely, increase in the value of (σ), results to a decrease in the basic reproduction number.

Figure 4.4 depicts the Sensitivity of the basic reproduction number to the parameters (β_1) and (ρ). It was shown that increase in parameters (β_1) and (ρ), results to a corresponding increase in the basic reproduction number indicating that higher transmission rates for subclinical infectious cattle and Progression rate from Exposed class enhance the spread of the disease.

Figure 4.5 illustrates the relationship between maximum rate of treatment (τ) and Progression rate from Exposed class (ρ) on the basic reproduction number. Increase in maximum rate of treatment decreases the basic reproduction number and increasing (ρ) leads to an increase in the basic reproduction number.

Figure 4.6 also shows the plot of Sensitivity of the basic reproduction number to the parameters (σ) and (μ). It shows that increase in the value of (σ) led to a corresponding decrease in the basic reproduction number and increase in (μ), results to an increase in the basic reproduction number.

CONCLUSION

This research utilizes mathematical modelling to evaluate the sensitivity analysis of bovine mastitis disease. The model provides a robust framework for understanding bovine mastitis disease transmission dynamics among the susceptible cattle population $S(t)$, Exposed population $E(t)$, Subclinical infective population $A(t)$, Clinical infective population $I(t)$, Chronic infective population $C(t)$, and the Recovered population $R(t)$. Sensitivity analysis was carried out and the per capital recruitment rate was seen as the most sensitive parameter followed by transmission rate for clinical infectious cattle. The findings of this study underscore the critical role of targeted interventions in achieving a Mastitis-free environment. Sensitivity analysis revealed the parameters most strongly influencing the dynamics of the disease. Notably, increases in certain parameters were shown to elevate the basic reproduction number (R_0), thereby sustaining transmission. Consequently, health policymakers and stakeholders are advised to prioritize interventions that enhance parameters with negative sensitivity indices, as these effectively reduce (R_0),and promote the eradication of infection.

Such measures are essential for fostering and promoting a healthier and more sustainable environment.

RECOMMENDATION

Based on the study, the following recommendations are suggested

1. Enhance Biosecurity Measures: Implement strict hygiene protocols and control visitor access to reduce transmission between cattle.
2. Improve Milking Hygiene: Regularly disinfect equipment and equipment and teat dips to minimize transmission during milking.
3. Target Treatment Strategies: Prioritize treatment of clinical cases and consider dry cow therapy to reduce periods.
4. Segregate high-Shedding Animals: Identify and separate or cull animals with high bacterial shedding to reduce transmission risk.

REFERENCES

Adewale, S.O; Podder, C.N; and Gumel A.B. (2009). Mathematical analysis of a Tuberculosis (T.B) Transmission Model with DOTS. Canadian Applied Mathematics, quarterly volume 17, November 1, Springer.

Adeyemi, M.O. and Oluyo, T.O. (2023). Mathematical modeling for the Control of Fly Borne Mastitis Disease in Cattle. Front. Appl. Math. Stat. 9:1171157. https://doi.org/10.3389/fams.2023.1171157.

Aligaz, A.A; and Munganga, J.M.W. (2018). Mathematical Modelling of the Transmission Dynamics of Contagious Bovine Pleuropneumonia with Vaccination and Antibiotic Treatment. Journal of Applied Mathematics. Vol.2019:1-10.

Arnold, M. (2019). Preventing Summer Mastitis in Heifers Begins with Horn Fly Control. UK College of Agriculture, Food and Environment, Cooperative Extension Service. http://entomology.ca.uky.edu/files/recs0/ent12-diary.pdf.

Arsenopoulos, K; Triantafillous, E; Filioussis, G; Papadopoulous, E. (2018). Fly Repellency Using Deltamethrin May reduce Intramammary Infections of Dairy Cows under Intensive Management. Comparative Immunology, Microbiology and Infectious Diseases. 61: 16-23.

Blowey, R.W. and Edmondson, P.W. (1995). Mastitis control in dairy herds. Pp. 29. Ipswich, Farming Press.

Capasso V, Serio G. (1978). A Regeneralization of the Kermack-Mckendric deterministic epidemic model. Math. Biosci 42:43-61.

Chitnis, N; James, M.H; and Cushing, J.M . (2008). Determining Important Parameters in the Spread of Malaria through the Sensitivity Analysis of Mathematical Model, Bulletin of Mathematical Biology. 70(5):1272-1296.

Diekman, O; Hesterbeek, J.A.P; Mertz, J.A.J (1990). On the Definition and the Computation of the Basic Reproduction Ratio, in Models for Infectious Diseases in Heterogenous Population, J. Math. Biol. Vol 28, pp. 365.

Fernanda Gomes, Maria Jose Saavedra, Mariana Henriques. (2016). An overview of the role of biofilms in Bovine Mastitis infection, Pathogens and disease, 74(3).

Jin Y, Wang W, Xiao S. (2007). An SIR model with a non-linear incidence rate. Chaos Solitions Fractals 34: 1482-1497.

National Mastitis Council (NMC). Current Concept of Bovine Mastitis, Fifth edition, National Mastitis council' Verona. 2011.

Odebiyi O.A and Oladejo J.K. (2024). Stability analysis of an HIV/AIDS model with saturated incidence. International Journal of Mathematical Analysis and Modelling. 7(1):75-98.

Odebiyi O.A, Oladejo J.K, Elijah E.O, Olajide O.A, Taiwo A.A, Taiwo A.J. (2024). Mathematical Modeling on Assessing the Impact of Screening on HIV/AIDS Transmission Dynamics. J. Appl. Sci. Environ. and Manag. 28(8): 2347-2357.

Odebiyi O.A, Oladejo, J.K, Yahaya A.A, and Elijah E.O. (2024). Analysis of HIV/AIDS Model with Nonlinear Incidence Function. International Journal of Research and Innovation in Applied Science, 9(4):317-341. Doi: https://doi.org/10.51584/IJRIAS.2024.904023.

Oluyo, T.O and Adeyemi, M.O. (2018). Sensitivity Analysis of Zika Epidemic Model. International Journal of Scientific and Engineering Research, 9(2):587-601.

Ruegg, P.L. (2012). New Perspectives in Udder Health Management, Vet. Clin. Food. Anim. 28:149-163.

Tewari, A. (2014). Bovine Mastitis: An Important Diary Cattle disease, Technical Report. Diaryman, 2014:62-65.

Van Den Driessche, P. and Watmough, J. (2002). Reproduction numbers and sub-threshold endemic equilibria for compartmental models of disease transmission. Mathematical Bioscience, 180:29-48. www.elservier.com/locate/mbs.

Wattiaux, M.A. (2021). Mastitis: The Disease and its Transmission. Diary essentials, Babcock Institute for International Diary Research and Development, University of Wisconsin-Madison.

Yeruham, I; Braverman,Y; Shipgel, N.Y; Chizov-Ginzburg, A; Seran, A; and Winkler, M. (1996). Mastitis in Diary Caused by Corynebacterium pseudotuberculosis and the Feasibility of Transmission by Housefly I. Veterinary quarterly, 18(3):87-89.

ISBN: 978-625-90157-4-3