AGRI-ECOSYSTEM MODELING AND SUSTAINABLE FARMING STRATEGIES

EDITOR

Mohamed Rami Berbache

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PREFACE

This book brings together interdisciplinary research that addresses contemporary challenges in agriculture, land management, and rural development under changing environmental and socio-economic conditions. The chapters collectively emphasize the importance of data-driven analysis, sustainable practices, and policy-relevant insights in strengthening agri-food systems and farmer livelihoods.

The chapter Spatio-Temporal Analysis of Changes in Agricultural Land Use in Semi-Arid Algerian Zones (2019–2023) Using Sentinel Images Processed on Google Earth Engine demonstrates the power of remote sensing and cloud-based geospatial platforms in monitoring land-use dynamics. By providing timely and accurate spatial information, it supports informed decision-making for sustainable land and water management in climate-sensitive regions.

Modeling and resource efficiency are further explored in Agri-Ecosystem Modeling: Dynamic Simulations for Policy and Practice and Climate-Smart and Sustainable Animal Feeding Strategies: Utilization of Agro-Industrial By-Products, Crop Residues, and Tropical Essential Oils. These chapters highlight how systems modeling and innovative feeding strategies can improve productivity while reducing environmental impacts and enhancing resilience across agricultural systems.

The final chapter, Promoting Cocoa Farming for Enhanced Farmers' Wellbeing in Nigeria, focuses on the human and economic dimensions of sustainability. By examining cocoa farming as a pathway to improved livelihoods, it underscores the role of inclusive agricultural development in achieving long-term social and economic wellbeing. Together, these chapters offer a holistic perspective on integrating technology, sustainability, and rural prosperity.

Editorial Team
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CHAPTER 1
SPATIO-TEMPORAL ANALYSIS OF CHANGES IN AGRICULTURAL LAND USE IN SEMI-ARID ALGERIAN ZONES (2019–2023) USING SENTINEL IMAGES PROCESSED ON GOOGLE EARTH ENGINE

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INTRODUCTION

Arid and semi-arid regions include a significant area of the Earth's surface and constitute one of the most delicate biological zones globally. They encompass over 41% of the Earth's terrestrial surface and accommodate over 2 billion individuals, nearly 60% of whom live in developing nations (Desta et al., 2020; Feng & Fu, 2013). These regions exhibit low and erratic rainfall, typically focused in a brief rainy season, with average annual precipitation generally not surpassing 600 mm (Goldblatt et al., 2017). Notwithstanding their severe climatic conditions, these environments are integral to the global food system, comprising over half of the world's agricultural land and making substantial contributions to food production, the seasonal carbon cycle, and the regulation of long-term climate dynamics (Husein et al., 2021; Wood et al., 2000). Semi-arid regions accommodate around 600 million smallholder farmers and pastoralists who depend predominantly on rain-fed agriculture and livestock rearing. These populations, frequently among the most vulnerable worldwide, are especially susceptible to climate variability, where even slight changes in rainfall patterns can significantly impact vegetation cover and jeopardize food security (Goldblatt et al., 2017). The vulnerability of these areas is intensified by the increase of irrigated agriculture due to increasing food demand, which further strains already scarce water resources (Pareeth et al., 2019)). Soil deterioration constitutes a significant challenge, jeopardizing agricultural output and consequently compromising food security (Begizew, 2021; Meng et al., 2019). Climate change forecasts substantiate these apprehensions, suggesting that worldwide arid regions may increase by an extra 5.8×10^6 km^2 by century's end under high greenhouse gas emission scenarios (Feng & Fu, 2013).

The interplay of environmental vulnerability and socio-economic reliance positions arid and semi-arid regions in the center of global discussions on food security, sustainable development, and climate adaptation. These regions are increasingly acknowledged as crucial areas where agricultural productivity, poverty alleviation, and land management intersect as essential development concerns.

The global community has emphasized the necessity of implementing sustainable land management methods, as precise assessments of cultivated land and crop yields are crucial for tracking agricultural output and predicting food emergencies (Samasse et al., 2018). Semi-arid regions are simultaneously experiencing significant alterations. Population expansion, swift urbanization, and increasing demand for agricultural products have heightened stress on land and water resources. The growth of irrigation in Asia and Africa has enhanced food production; nevertheless, it has also led to significant groundwater depletion, reduced water tables, and soil salinization (Kuper et al., 2016; Saadi et al., 2020). Furthermore, pastoral systems and rangelands are becoming marginalized due to the transformation of grasslands into agricultural lands, resulting in detrimental effects on biodiversity and the livelihoods of pastoral populations (Belhadj et al., 2023). The convergence of these elements underscores the pressing necessity for effective monitoring methods to document land use and land cover changes in semi-arid regions.

Remote sensing as a method for overseeing semi-arid agriculture Recent advancements in remote sensing and geographic information systems (GIS) provide unparalleled opportunities for monitoring and managing agricultural dynamics in vulnerable situations. The Sentinel missions of the European Space Agency have shown to be highly effective instruments for identifying spatio-temporal alterations in land cover. Launched in 2015, Sentinel-2 offers high-resolution multispectral imagery (10–20 m) with a five-day revisit frequency, representing a significant enhancement over earlier missions like Landsat (Trivedi et al., 2023). The constellation comprises supplementary narrow bands in the red-edge and near-infrared spectrum, which exhibit heightened sensitivity to vegetation health and agricultural phenology (Kganyago et al., 2020). Simultaneously, Sentinel-1 radar imaging facilitates the uninterrupted surveillance of agricultural lands by mitigating the constraints posed by cloud cover, which is especially pertinent for irrigated crops in semi-arid areas (Amazirh et al., 2021).

The amalgamation of Sentinel images with cloud-based systems like Google Earth Engine (GEE) has transformed the ability to assess agricultural dynamics.

GEE facilitates extensive processing of satellite data, integrates multi-sensor datasets, and employs machine learning techniques for land classification and change detection (Ioannidou et al., 2022). Research conducted in Africa and Asia has shown that Sentinel and GEE are effective for mapping croplands, estimating crop yields, monitoring irrigation practices, and assessing vegetation phenology with high precision (Abubakar et al., 2023; Imanni et al., 2022; Kobayashi et al., 2019). In Morocco's Tadla irrigated perimeter, the integration of Sentinel-1 and Sentinel-2 data with Random Forest classifiers facilitated early and accurate crop type mapping in a highly fragmented agricultural terrain (Htitiou et al., 2020). Comparable implementations in Ethiopia, Sudan, and Nigeria validate the significance of these instruments for sustainable resource management in semi-arid environments (Altoom et al., 2025; Eisfelder et al., 2024; Eze, 2023).

These methodological advancements are especially pertinent as global food insecurity escalates due to conflicts, climate change, and socio-economic disparities (Abdivaitov & Strobl, 2023). Remote sensing furnishes decision-makers with critical information for formulating adaptive strategies that harmonize agricultural development with ecological conservation.

The context of Algeria Semi-arid and dry regions dominates Algeria's national territory and are crucial to the country's agricultural plans. The Biskra region, situated near the entrance to the Sahara, exemplifies these processes. Biskra, recognized as the national capital of greenhouse horticulture and date palm agriculture, holds a pivotal position in national food security and export markets (Hemidi & Laamari, 2020; Oukil et al., 2023). This development is occurring concurrently with significant environmental issues, such as groundwater overexploitation, soil salinization, and rangeland degradation (Belhadj et al., 2023; Kuper et al., 2016).

The circumstances of Algeria can be encapsulated by four interconnected issues:

- Decline of rain-fed crops attributable to erratic precipitation and rising drought incidence.
- Expansion of irrigated regions, facilitated by groundwater extraction and agricultural policies that advocate for drip irrigation.

- Urbanization and land pressure, characterized by the encroachment of urban sprawl and infrastructure development on fertile farmland.
- The risk of overexploitation of water resources, with groundwater extraction significantly beyond renewable capacity, jeopardizes long-term sustainability.

Study Objectives

This chapter seeks to identify and quantify the principal alterations in agricultural land use in the Biskra region from 2019 to 2023.

Assess the contributions of Sentinel images and Google Earth Engine for the multi-temporal identification of agricultural dynamics in a semi-arid environment.

- Examine the ramifications of these alterations on food security, sustainability of natural resources, and the resilience of agricultural systems in Algeria.

This study positions Biskra within the wider context of global semi-arid challenges, aiming to emphasize the potential of spatial technologies for agricultural monitoring and the pressing necessity for integrated land management strategies that harmonize production demands with ecological sustainability.

1. METHODOLOGIES AND TECHNICAL APPROACHES

The methodological approaches for studying semi-arid agricultural lands mainly rely on the integration of remote sensing data with field information in a GIS environment. This integration allows for the assessment of soil productivity, erosion, surface runoff, groundwater potential, its quality, agricultural land suitability, and the development of land use planning strategies. The advantage of these methods, primarily based on remote sensing, is that they require minimal effort for any agency to prepare a similar sustainable agricultural development plan (Balasubramani, 2020).

Remote sensing data allows for rapid and efficient mapping of agricultural land cover, supporting various global agricultural monitoring applications. However, these technologies depend on reliable ground truth data to ensure their accuracy (Remelgado et al., 2020).

Evaluation methods use rigorous validation approaches, such as selecting representative polygons, generating randomly superimposed points, and using Sentinel-2A images at 10m or Google Earth as ground truth (Alkhalil et al., 2020).

Phenological analysis constitutes a crucial methodological approach for monitoring semi-arid crops. Time series of satellite data are particularly well-suited for monitoring the spatiotemporal behaviour of plant phenology (Lebrini et al., 2021). Remote sensing data provides broad and continuous observations that characterise terrestrial changes, with satellite time series offering strong potential for understanding and detecting phenological changes due to consistent and frequent coverage (Lebrini et al., 2021; Li et al., 2014).

Modern methodological approaches also include the development of automated change detection systems with high temporal frequency (bi-weekly) and spatial resolution (10 to 30 m) for monitoring the dynamics of ecosystem services. These systems take advantage of the emerging availability of high spatio-temporal resolution Earth observation data, including the Copernicus Sentinels, the DLR's TanDEM-X, and the NASA/USGS Landsat (Baade et al., 2021).

For the sustainable management of semi-arid lands, the methodologies integrate the mapping of land use practices at the thematic resolution of individual crops, using, for example, 13 images generated by Sentinel-2 satellites. The FAO's free software is used to overlay satellite data images with climate data for agricultural water resource management (hafyani et al., 2021).

Monitoring methodologies also integrate satellite-supported inverse biophysical modelling, developed at NASA and adapted to specific study regions. These approaches use intra- and inter-annual Landsat images for the detection of agricultural lands in the context of global climate change (Karnieli et al., 2012).

The modern technical approach combines several spectral indices and predictive models. An innovative integration of the Water Ratio Index (WRI), the Normalised Difference Chlorophyll Index (NDCI), LULC mapping, and Cellular Automata-Markov modelling with temperature fluctuations allows for monitoring the dynamics of irrigated lands using high-resolution satellite imagery (30m).

This multi-model fusion bridges the gap between biophysical water availability, vegetation health, land transition trends, and future irrigation scenarios (Ali et al., 2025).

2. THE GEOGRAPHICAL LOCATION OF THE STUDY AREA

Biskra is a medium-sized city located in southeastern Algeria, strategically positioned at the gateway to the Sahara Desert in an oasis area (Bendjedidi et al., 2019; Rais et al., 2019). The city is located approximately 430 km south of Algiers and is known as the "gateway to the desert" (Bendjedidi et al., 2019; Saker & Akakba, 2024). The geographical coordinates of Biskra are precisely located at 34°48' North latitude and 5°44' East longitude (Boumessenegh & Dridi, 2021; Rais et al., 2019), with an altitude ranging between 82 and 88 meters above sea level (Oukil et al., 2023; Rais et al., 2019).

The province (wilaya) of Biskra covers an area of 20,986 to 21,671 km² according to sources (Agadi et al., 2023; Selmane & L'Hadj, 2016), and includes 33 municipalities spread across 12 districts. The region is home to an estimated population of over 820,000 inhabitants (Selmane & L'Hadj, 2016). Biskra occupies a unique geographical position as a transition zone between the folded domains of the Saharan Atlas to the north and the flat, desert expanses of the Sahara to the south (Laouar et al., 2023). This position makes it a crucial buffer zone between the north and south of the country. The region features four distinct geomorphological elements: mountains, plains, plateaus, and depressions (Agadi et al., 2023; Mohammed et al., 2023). The territory of Biskra is bordered by several wilayas: Batna and M'sila to the north, Ouargla and El-Oued to the south, Khenchela to the east, and Djelfa to the west. The region is crossed by various wadis and temporary watercourses that flow into the Chott Melghir depression, notably the Oued El Arab, which constitutes the main watercourse of the region (Agadi et al., 2023).

3. THE CLIMATIC AND ENVIRONMENTAL CHARACTERISTICS

Biskra is characterised by a hot desert climate (BWh) according to the Köppen-Geiger classification, typical of Saharan regions (Besbas et al., 2022; Lahmar et al., 2019). This classification reflects very hot summers and mild winters (Kottek et al., 2006; Rais et al., 2021). Temperatures show significant variations throughout the year. In summer, average temperatures reach 34.8°C to 40.2°C in July, the hottest month (Besbas et al., 2022; Rais et al., 2021). In winter, average temperatures range between 11.5°C and 16.7°C in January (Rais et al., 2021; Selmane & L'Hadj, 2016). Thermal variations can reach 22.7°C between seasons and up to 22°C between day and night (Bengouga et al., 2019; Rais et al., 2021).

Precipitation is low and irregular, varying between 106.7 mm and 148 mm per year according to sources (Degui et al., 2024; Nafissa et al., 2020; Saadi et al., 2020). In some peripheral areas, precipitation can drop to between 100 and 300 mm annually (Bengouga et al., 2019). The Sahara region as a whole generally does not exceed 130 mm of annual precipitation (Homrani et al., 2020). The dry period extends almost throughout the year, with an almost total absence of precipitation in summer (Saadi et al., 2020; Selmane, 2015; Selmane & L'Hadj, 2016).

The relative humidity exhibits strong seasonal variations. It reaches its maximum in December with 60.7% to 89% depending on the areas, while in summer it drops drastically to 12% to 26.5% in July (Boumessenegh & Dridi, 2021; Rais et al., 2021). The average annual relative humidity ranges from around 42.9% to 47% (Abdennour et al., 2019; Bengouga et al., 2019; Nafissa et al., 2020). The region enjoys exceptional sunshine with an average annual duration of 9.32 hours and a global irradiation of approximately 5545 Wh/m² on a horizontal plane (Lahmar et al., 2019). The intensity of solar radiation varies from 7680 Wh/m² in July (up to 12 hours per day) to 2712 Wh/m² in December (7 hours per day) (Boumessenegh & Dridi, 2021). Potential evapotranspiration is very high and can reach 10 to 20 times the amount of precipitated water, a typical characteristic of arid environments (Saadi et al., 2020). This high evaporation, combined with low precipitation, contributes to the marked aridity of the region (Selmane, 2015; Selmane & L'Hadj, 2016).

The De Martonne aridity index confirms the arid nature of the region with an average value of 5.64 (Benamor & Benabbas, 2019). Biskra is even classified as hyperarid with a mild winter in the bioclimatic zone (Degui et al., 2024).

4. THE AGRICULTURAL NATURE AND MAIN CROPS

The Biskra region is characterised by the predominance of an oasis farming system based on date palm cultivation, practiced for centuries in this region (Hemidi & Laamari, 2020). The Ziban area is famous for the extent of its oases, with five million date palms (Berkouk et al., 2020). The total area dedicated to agriculture represents approximately 1,652,751 hectares, which is 77% of the total area of the district (Hemidi & Laamari, 2020). In the Tolga region, for example, 74.87% of the useful agricultural area is dedicated to date palms (Djelloul & Djamel-Eddine, 2012).

Biskra holds a remarkable economic position, ranking second in Algeria for agricultural production with approximately 1.24 billion euros in 2012. The region produces 37% of the dates cultivated in Algeria, notably the deglet nour variety intended for domestic and export markets. Since the 1980s, the region has experienced a rapid expansion of greenhouse horticulture, covering nearly 100,000 greenhouses (approximately 4,000 hectares) in 2010 (Kuper et al., 2016). This area increased from 1,370 hectares in 1999 to 4,050 hectares in 2013. Although it occupies only 4% of the irrigated land in the region, greenhouse production accounts for more than half of the national greenhouse crop market (Oukil et al., 2023).

The main greenhouse crops include tomatoes (representing 25% of national production and 34% of the regional greenhouse area), peppers, chillies, eggplants, melons, and watermelons (Kuper et al., 2016; Oukil et al., 2023). These crops arrive early on domestic markets thanks to favourable climatic conditions (Kuper et al., 2016).

The region presents a diversification of production systems with three dominant systems: a date production system, a vegetable farming system, and a mixed system combining dates and vegetables (Abdennour et al., 2019). The climatic conditions and vast agricultural lands of Biskra are favourable for the cultivation of various types of plant productions (Nafissa et al., 2020).

In peripheral areas, agropastoralism remains an important activity, with a notable increase in the sheep population, which rose from 20,475 heads in 1996 to 52,143 in 2019. However, the steppe rangelands have undergone rapid degradation over the past three decades, with their area decreasing in favour of marginal crops (Belhadj et al., 2023).

5. THE PROBLEMS OF AGRICULTURAL LAND IN THE REGION

The Biskra region faces a major problem of overexploitation of groundwater resources. The use of groundwater for irrigation is estimated at approximately 1.2 km^3 per year, which represents 467% of the volume of exploitable renewable groundwater resources (0.26 km^3/year) (Kuper et al., 2016). This overexploitation has resulted in a general decrease in piezometric levels of 90 meters over the past 40 years (Saadi et al., 2020).

Farmers are facing declining groundwater levels and frequently have to deepen their wells (Kuper et al., 2016). This intensification generates several problems: the regular drop in water levels, the increase in pumping costs, and the weakening of artesianism (Saadi et al., 2020). Soil salinisation has accelerated in recent years in irrigated areas due to the increased use of groundwater to meet irrigation needs (Abdennour et al., 2019). Environmental problems are acute and linked to the current dynamics of agricultural practices, notably the depletion of the water table in the Ziban (Bouchemal, 2021).

The efficiency of water and land use remains very low, these problems being exacerbated by low-cost water that is pumped for free, low annual rainfall estimated at less than 250 mm, and the intermittent transfer of greenhouse construction to escape soil disease problems (Ariom et al., 2022). The region also faces contamination problems. Some farmers irrigate their crops with drainage water mixed with wastewater, and the wastewater is discharged into agricultural drains and then into the Oued Djedi (Kouider et al., 2025). An analysis of the most exploited boreholes reveals a weak correlation of nitrates with other parameters, confirming their origin linked to the proximity of agricultural lands and industrial areas (Zohra et al., 2024).

Over the past three decades, steppe rangelands have undergone rapid degradation due to climatic factors and human activities such as overgrazing (Belhadj et al., 2023; Miloudi & Remini, 2018). The area of grazing lands has decreased in favour of marginal crops (Belhadj et al., 2023).

6. MATERIALS AND METHODS

Overview Of The Workflow

The study followed a comprehensive workflow that includes: data collection and preparation → setting up training and validation points → building classification models (RF, SVM, CART) on the Google Earth Engine (GEE) platform → accuracy assessment → analysis of spatio-temporal changes (2019–2023). The processing and classification were carried out within the GEE environment to leverage its capabilities in handling large time series and Sentinel-2 data. (Ganjirad & Bagheri, 2024a).

Collection and Preparation of Training and Validation Data

Image sources: Sentinel-2 images (surface reflectance or composite time series) were used as the primary data for classification, supported by high-resolution images (Google Earth) for field verification and labelling.(Nasiri et al., 2022).

Setting up training points: Training points were selected for each land use category (e.g., agricultural lands, built-up areas, bare soil, water bodies, natural vegetation cover). The training point selection protocol was followed, ensuring: representation of variation within the class, balanced geographic distribution, and avoiding reliance solely on old reference data. The literature recommends creating a classification legend and field images, if possible, to improve the quality of the training data (Moraes et al., 2024a).

Validation points: An independent set of validation points (different from the training points) was randomly collected and weighted according to the area of each class to be used later. The presence of an independent validation set is essential for estimating the true performance of the model (Moraes et al., 2024a).

Pre-Processing & Feature Extraction

Cloud and temporal correction: Before classification, Sentinel-2 images were processed for time series to be relatively cloud-free using compositing methods (median/percentile compositing) or cloud removal algorithms available in GEE.

Spectral and temporal features: Important spectral indices (such as NDVI, NDWI, NDBI when needed) were derived, in addition to temporal statistics (mean value, maximum/minimum) for each pixel to be used as inputs in classifiers. The literature shows that combining spectral and temporal indices improves classification accuracy, especially in semi-arid environments.

Classification Algorithms and Experiment Setup

Selected algorithms: We use three common algorithms for comparison:

Random Forest (RF): A non-linear, clutter-resistant algorithm that works well with multi-dimensional spectral inputs and often delivers superior performance in LULC studies on Sentinel-2.

Support Vector Machine (SVM): Effective with high-dimensional datasets and the kernel parameters (kernel, C, gamma) can be adjusted for optimal performance.

Classification and Regression Trees (CART): A simple tree algorithm that serves as a good baseline and has high interpretability.

Experiment setup: The same training point sets are used for each algorithm to ensure a fair comparison, with the training data divided into internal training sets if necessary (cross-validation) to optimise hyperparameter tuning. All models were executed/compared within the GEE (Python API) environment. (Ganjirad & Bagheri, 2024b).

Accuracy Assessment

Confusion matrix: It was created by comparing the classification map with the validation data. From the main outputs: the number of pixels for each transformation (observed vs predicted).

Calculated accuracy indicators:

Overall Accuracy.

Kappa coefficient.

Producer's Accuracy and User's Accuracy.

Important practices: Using a sufficiently validated sample in terms of quantity and distribution for each category and providing confidence intervals, if possible, for accuracy estimates. The literature defines precise evaluation protocols and explains the limitations of interpreting Kappa compared to other indicators (Nicolau et al., 2024).

Detection And Analysis of Spatiotemporal Changes (2019–2023)

Post-classification change detection: After producing classified annual maps, the maps are compared in pairs or over the time series to create change matrices and identify transformations (e.g., from agricultural land to buildings). This method is practical and common because it directly compares classified categories.

Trend analysis: Indicators of changing areas for each category are calculated over the years, and trends of increase/decrease are analysed statistically (timeline, annual rates). Spatial density analysis can also be used to identify hotspots of change.

Implementation on Google Earth Engine (GEE) Technical Notes

Execution environment: Time series aggregation, feature extraction, model training, and accuracy evaluation were performed using scripts on GEE (JavaScript / Python). GEE accelerates processing for large areas and provides direct access to the Sentinel-2 archive (Ganjirad & Bagheri, 2024c).

Supplementary verification: Whenever possible, field verification and/or the use of independent reference sets (such as local databases or recent high-resolution images) are recommended to enhance confidence in the results (Moraes et al., 2024b).

Table 1. Evolution of Land Use and Land Cover (LULC) classes during 2019–2021 (km² and %)

Classes	LULC 2019	LULC 2020	LULC 2021	LULC 2022	LULC 2023
Tree cover km²	245.10599718489300	245.10599718484900	320.09043228818900	17.37632003	12.65449531
Grassland km²	1722.71279688002000	1722.71000000000000	1665.17000000000000	5867.981495	5755.226647
Cropland km²	585.36469293452100	585.36469293495100	733.37000000000000	1448.794525	1534.028526
Built km²	96.34148083156230	96.34148083128600	117.71240102567600	120.2940277	126.878428
Bare soil km²	18744.12195162680000	18744.12000000000000	18556.05000000000000	14050.53676	14075.63042
Water bodies km²	5.24259703695579	5.24259703695722	4.48425740213009	2.268418949	2.189567125

7. LULC MAPS OF BISKRA FOR THE PERIOD 2019–2021

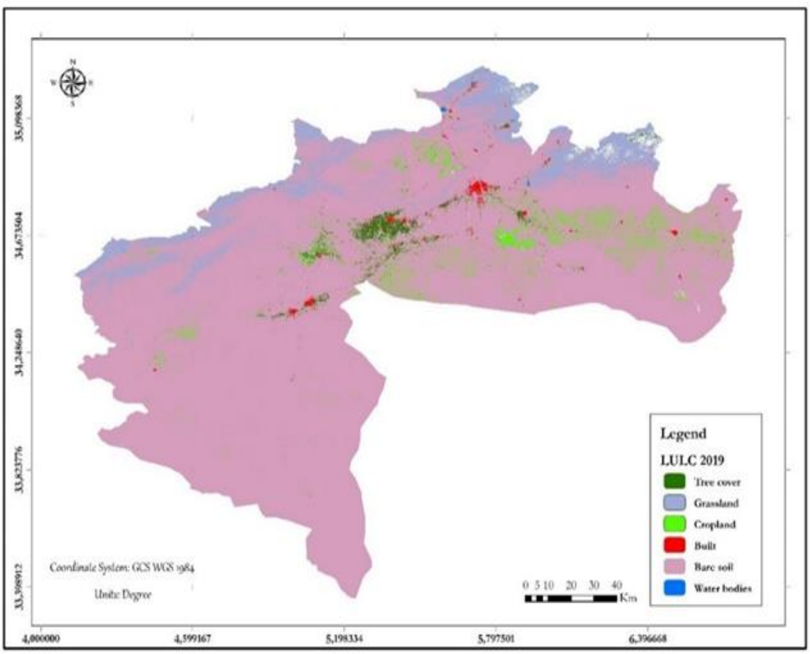

Figure 1a. LULC map of Biskra in 2019

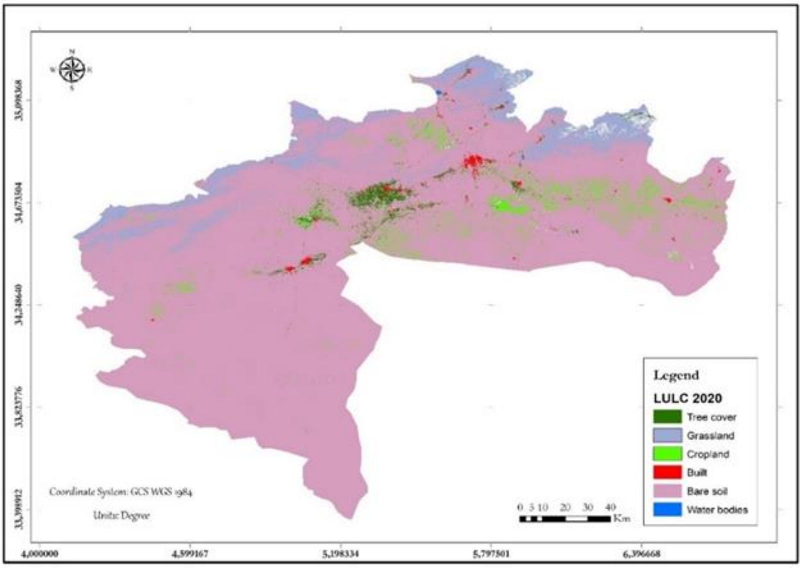

Figure 1b. LULC map of Biskra in 2020

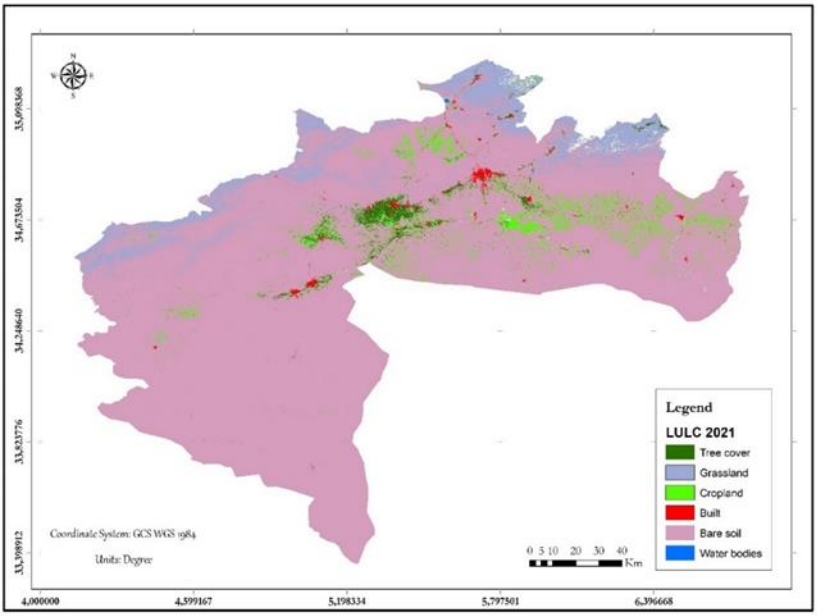

Figure 1c. LULC map of Biskra in 2021

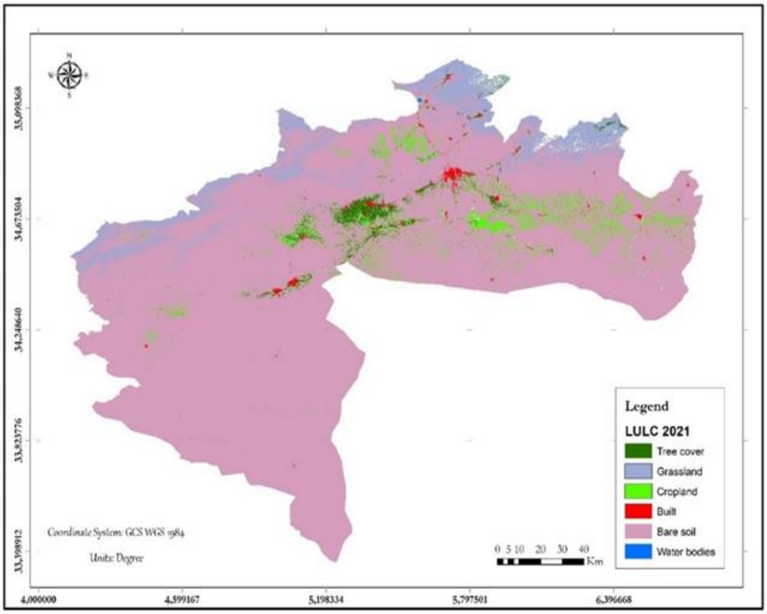

Figure 1c. LULC map of Biskra in 2021

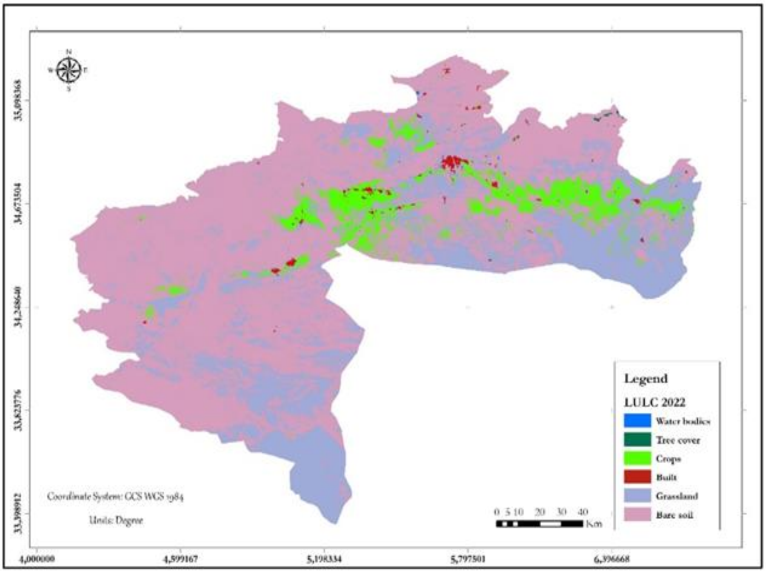

Figure 1d. LULC map of Biskra in 2022

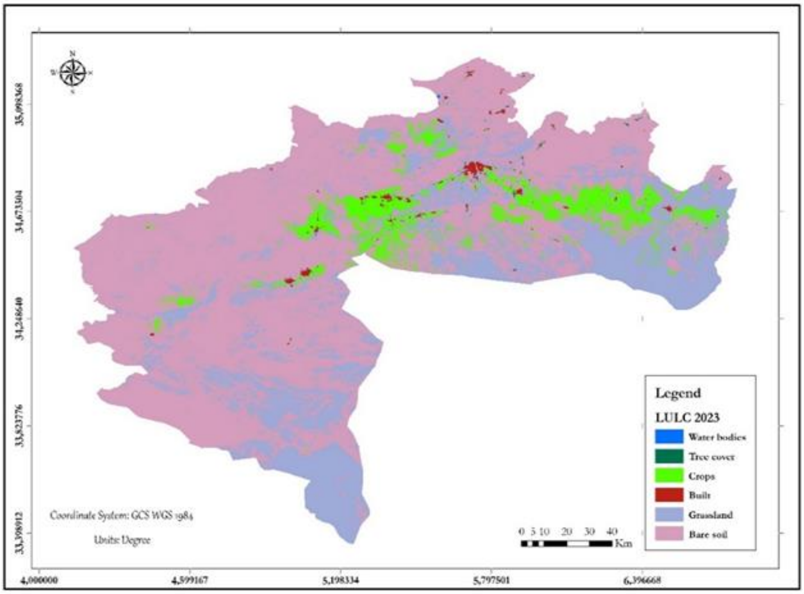

Figure 1e. LULC map of Biskra in 2023

7.1 Comparative Scientific Analysis of Maps From 2019 to 2023

This analysis is based on the submitted document regarding the spatiotemporal analysis of changes in agricultural land use in the semi-arid regions of Algeria (Biskra region) during the period 2019-2023, using processed Sentinel images on Google Earth Engine. The document includes a table showing the development of land use and land cover (LULC) categories from 2019 to 2021 (in square kilometres and percentages), and LULC maps for the years 2019 to 2023 (Figures 2a to 2e). However, the detailed description in the document focusses on the period 2019-2021, while recent similar studies (such as those for the Touggourt area in Biskra Province) are referenced to complete the analysis for the years 2022 and 2023, where similar trends in spatiotemporal changes are observed. The main LULC categories include: bare soil, farmland, tree cover, grassland, built-up areas, and water bodies. The analysis focusses on spatiotemporal changes and the influencing natural and human factors.Description of the maps for each year: Based on the document and related studies.

Map of 2019 (Figure 2a): Shows a significant dominance of bare soil, reflecting the dry to extremely dry conditions in the region. Agricultural land and tree cover are limited, with pastures and built-up areas around major cities like Biskra. Water bodies are scarce due to the lack of rainfall. 2020 Map (Figure 2b): A noticeable increase in agricultural land and tree cover is observed, especially in the central and northeastern regions, linked to the expansion of irrigated agriculture (such as palm and olive farms). The built-up areas are growing moderately around urban centres, with a relative stability of bare soil. Map 2021 (Figure 2c): It highlights a greater expansion of agricultural lands at the expense of bare soil and degraded pastures, with a slight increase in tree cover. Pastures are significantly decreasing, and water bodies are diminishing due to groundwater extraction. The built-up areas continue to grow, reflecting demographic pressure. Map 2022 (Figure 2d): Based on the ongoing trends from similar studies (such as the Tulkha study 2000-2023), the expansion of built-up and agricultural areas at the expense of bare soil is expected to continue, with a slight decrease in overall vegetation cover due to urbanisation. The focus on intensive agriculture continues, but with risks of water resource degradation. Map 2023 (Figure 2e): shows an intensification of previous trends, with an increase in built-up areas by up to 29% compared to previous periods (based on Tolga data), a decrease in bare soil by about 24%, and a relative stability or slight decrease in vegetation cover (approximately -0.26%). Agriculture remains dominant, but with impacts on the ecological balance.

Comparison Between the Years

From 2019 to 2020: a noticeable increase in agricultural land and tree cover, driven by irrigated agriculture and the development of new areas. This reflects national policies to expand desert agriculture. Moderate growth in the built-up areas around Biskra, linked to agricultural infrastructure (roads, warehouses, greenhouses). Stability of bare soil, with a slight decrease in pastures and water bodies due to agricultural use.

From 2020 to 2021: Greater expansion of agricultural land at the expense of bare soil and pastures, with an increase in tree cover (especially palm and olive trees) that withstand climatic conditions.

A significant decline in pastures, threatening traditional pastoral economies, and a reduction in water bodies due to lack of rainfall and groundwater depletion. Continuous growth of built-up areas, leading to the fragmentation of ecosystems and loss of biodiversity.

From 2021 to 2022: Continuation of trends with an increase in built-up and agricultural areas, but with signs of a slight decrease in total vegetation cover (based on a longitudinal study). Bare soil is decreasing, indicating a greater land conversion. The impact of agricultural policies continues, but with increasing environmental risks such as water depletion.

From 2022 to 2023: reinforcement of urban expansion (about +29% in built-up areas compared to previous periods), with a decrease in bare soil (-24%) and stability or slight decline in vegetation cover (-0.26%). This reflects the pressures of urbanisation on agriculture, with rising land surface temperatures (LST) due to the loss of vegetation.

Main trends: Agricultural expansion: An increase in agricultural land and tree cover from 2019 to 2021, with a slight continuation until 2023, driven by the cultivation of palm and olive trees. However, recent studies indicate a slight decrease in total vegetation cover due to urbanisation. Urban growth: Continuous growth in built-up areas, linked to population increase and the need for infrastructure, leading to the fragmentation of ecosystems. Environmental degradation: a decrease in pastures and water bodies, with bare soil stabilising initially and then declining. This is associated with groundwater depletion, land degradation, and rising temperatures. Influencing factors: Human factors (agricultural policies, urbanisation) dominate, with natural influences (drought). Studies indicate an impact on surface temperatures, where vegetation reduces heat, while urbanisation increases it.

The comparative analysis shows a dual dynamic: agricultural and economic expansion versus environmental threats such as the loss of pastures and water depletion. From 2019 to 2023, the region shifted towards greater agricultural and urban density, with the continued dominance of bare soil. Sustainable policies are recommended to maintain ecological balance, such as regulating water extraction and protecting pastures. For a more accurate analysis, it is preferable to access complete quantitative data for the years 2022 and 2023 from the original table or maps.

7.2 LULC Growth Index: Relative Change From 2019 Baseline

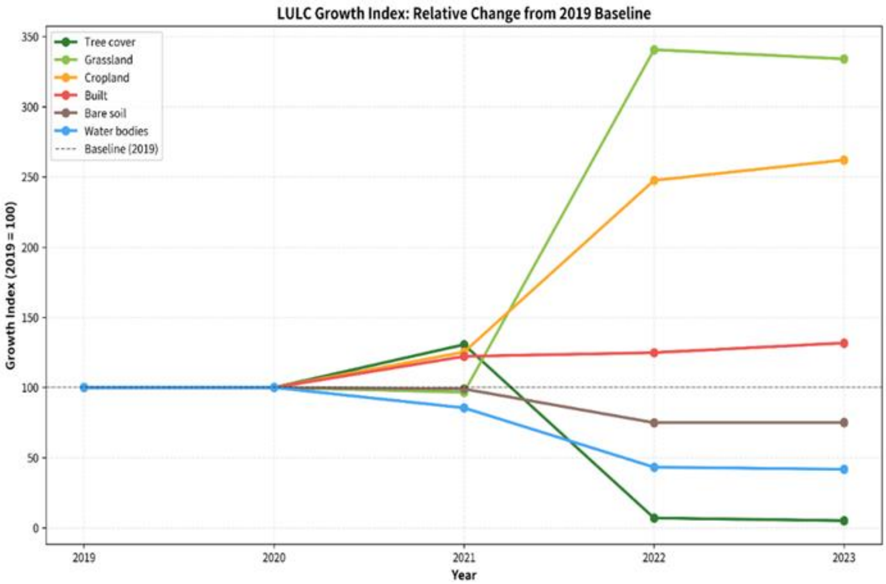

Figure 2 LULC growth index: relative change from 2019 baseline

The (figure 3) shows how the Land Use and Land Cover (LULC) growth index has changed over the past five years (2019–2023) in six main categories, with 2019 as the starting point. The research delineates substantial changes in land use and cover. Grasslands, in particular, showed the biggest increase, going up from 2021 to 2022 and then leveling off at about 340% of the baseline. This increase could mean that pastures are getting bigger, that degraded land is being restored, or that the weather is changing in a way that makes grazing easier. These kinds of changes could make rangelands more diverse and productive for livestock, but they might also have an effect on other types of land cover. Agricultural land showed the second biggest increase, steadily growing from 2020 to 2023 and reaching about 260% of the baseline. This trend shows that agriculture is still growing, probably because there is a lot of demand for food and land that can be farmed. This could put more strain on natural resources while also helping to grow food. By 2023, urbanized areas had grown to almost 130% of their original size, which shows how important it is to plan ahead to make sure there are enough services and infrastructure.

At first, the tree cover grew, but by 2022, it was almost gone. This could mean deforestation, land conversion, or environmental degradation, all of which are bad for biodiversity and ecosystem services. Bare soil changed slightly over time, eventually dropping to about 75% of the baseline level. This trend could be caused by changes in how land is used, restoration efforts, or erosion dynamics, which means that land management practices need to get better. Over time, water bodies shrank to only about 40% of the baseline. This could have been caused by drought, development, changes in rainfall patterns, or changes in how water is used. These changes could have a big effect on the quality, quantity, and ecosystems of water. Changes in how land is used and covered can have a big effect on ecosystems, farming, cities, water resources, the local climate, and biodiversity. So, it is very important to make sure that planning rules fairly balance the needs of development with the need to protect the environment.

7.3 Net Change Analysis: LULC Transformations

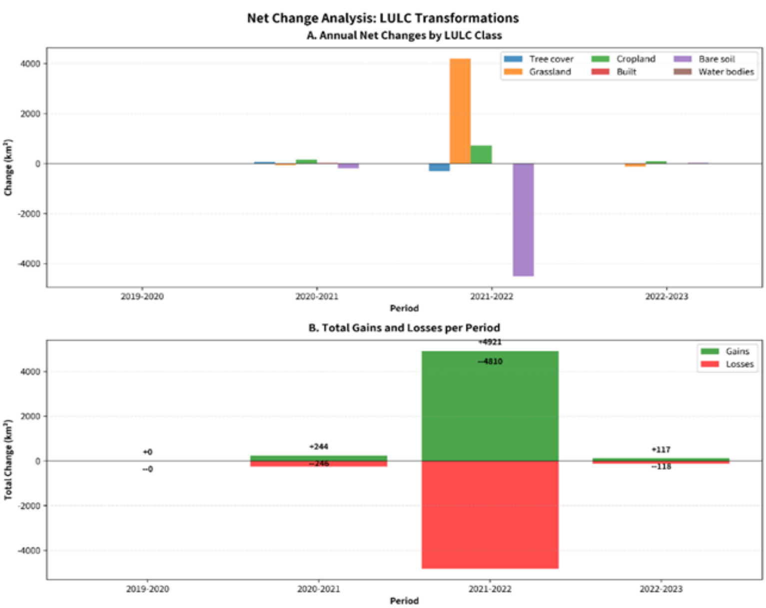

Figure 3. Net change analysis LULC transformations

Part (A) of the (figure 4) illustrates the annual net alterations in six principal land use and land cover (LULC) categories: tree cover (blue), agricultural land (green), grassland (orange), built-up areas (red), bare soil (purple), and water bodies (brown). The horizontal axes denote the time intervals (2019-2020, 2020-2021, 2021-2022, 2022-2023), whereas the vertical axis indicates the variation in square kilometers (ranging from -4000 to +4000 km^2). Between the periods 2019-2020, 2020-2021, and 2022-2023, the net alterations across all categories are negligible, nearing zero, signifying relative stability in land use and land cover (LULC). In 2020-2021, a little increase in agricultural land (about +100 km^2) was noted, alongside a minor decrease in built-up areas and bare soil. The 2021-2022 period, however, exhibits substantial alterations: a considerable increase in grasslands (about +3200 km^2, as indicated by the length of the orange bar), a moderate rise in agricultural land (around +500 km^2), a notable decrease in bare soil (around -3500 km^2), and a moderate decline in tree cover (about -500 km^2). Developed regions and aquatic environments exhibit minor adverse alterations.

Part (B) of the (figure 4) illustrates the aggregate gains (green, positive) and losses (red, negative) for each period, representing gross changes rather than net alterations. The periods of 2019-2020, 2020-2021, and 2022-2023 exhibit a near equilibrium between gains and losses, characterized by minimal figures (for instance, +244 km^2 gains and -246 km^2 losses in 2020-2021, culminating in a net change of approximately -2 km^2; and +117 km^2 gains and -118 km^2 losses in 2022-2023, resulting in a net change of -1 km^2). The 2021-2022 period is notable for its changes, yielding total gains of +4921 km^2 and losses of -4810 km^2, culminating in a marginal positive net change of +111 km^2. This signifies significant transformations, wherein losses and profits are considerable yet comparatively equitable. This pattern indicates that, during these periods, area changes largely occurred as reciprocal exchanges rather than unidirectional trends. Despite substantial gross gains and losses, the limited net change suggests that spatial transformations were dynamic yet largely balanced.

7.4 Land Use Distribution: 2019 Vs 2023

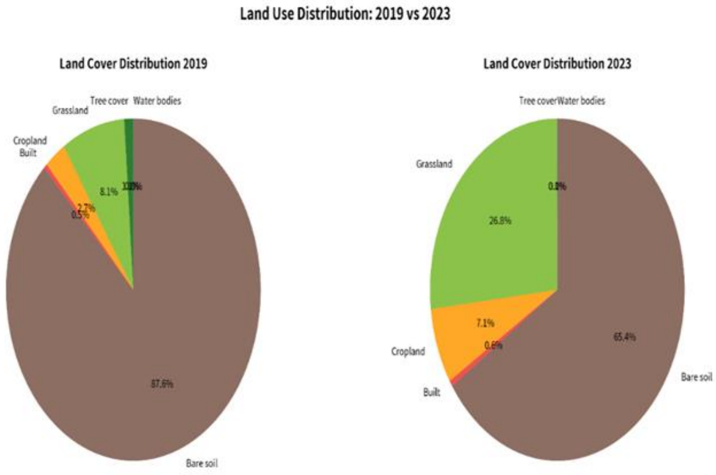

Figure 5. Land use distribution: 2019 vs 2023

The (figure 5) shows a comparison of land cover distribution for 2019 and 2023 using pie charts. Each segment shows the percentage of total area for six main land use and land cover categories: bare soil (brown), grassland (green), tree cover (dark green), cropland (orange), built-up areas (red), and water bodies (blue). This picture shows the percentage changes over four years, giving a general idea of how land use has changed in the area being studied, which seems to be semi-arid based on the fact that there is a lot of bare soil. In 2019, there was 87.6% bare soil, 8.1% crops, 2.7% tree cover, 1.0% grassland, and 0.5% water bodies. Built-up areas made up only 0.0% of the land. This distribution indicates a land system with limited productivity, maybe affected by factors such as drought or desertification. By 2023, the amount of bare soil had dropped to 65.4%, while the amount of grassland had risen to 26.8% and the amount of tree cover had risen to 7.1%. On the other hand, agriculture dropped to 0.6%, while built-up areas and bodies of water stayed at very low levels (0.0% each).

7.5 Detailed Analysis Of LULC Trends 2019-2023

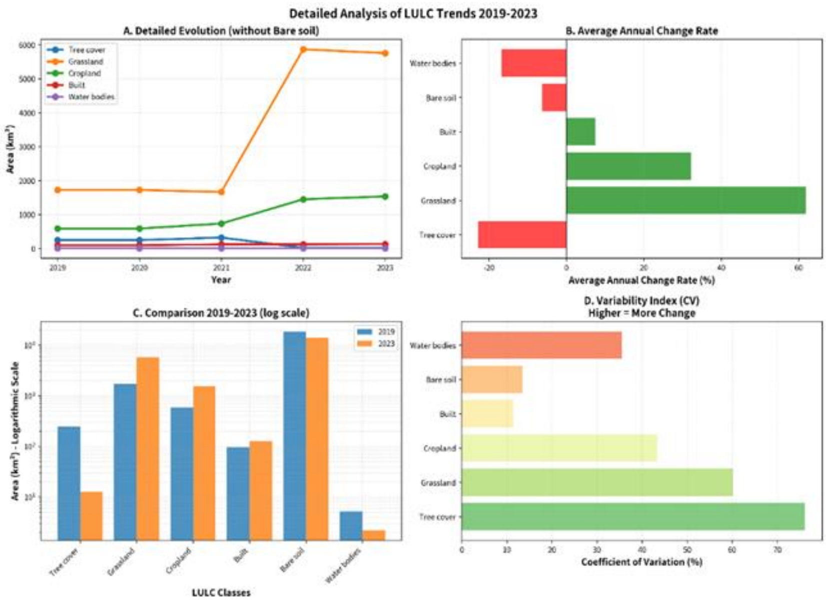

Figure 6. Detailed analysis of LULC trends 2019-2023

The (figure 6) provides a detailed analysis of trends in Land Use and Land Cover (LULC) from 2019 to 2023, divided into four main sections: (A) detailed development of areas (excluding bare soil to avoid visual dominance), (B) average annual rate of change, (C) a comparison between 2019 and 2023 on a logarithmic scale, and (D) the Coefficient of Variation (CV). The six categories are represented as follows: Tree cover (blue), grassland (orange in A, green in B and D), cropland (green in A, yellow in D), built areas (red), bare soil (not included in A), and water bodies (purple).

In section (A), the line chart illustrates the development of areas in square kilometers. Grasslands show a sharp increase from about 2,000 km² in 2019 to over 5,500 km² in 2023, with a notable jump between 2021 and 2022. Tree cover rises gradually from about 500 km² to 1,500 km². Cropland remains relatively stable at 1,000 km² with a slight decrease at the end. Built areas and water bodies remain very low (less than 100 km²).

Section (B) depicts the average annual rates of change as percentages. Tree cover and grassland show positive growth (around +40% and +50%, respectively), while cropland, bare soil, built areas, and water bodies show declines (about -20% for cropland and -10% for bare soil).

In (C), the logarithmic comparison highlights the shifts: a significant increase in grassland (from about 10^2 to 10^3 km²) and tree cover, versus a decrease in bare soil (from 10^4 to less) and cropland.

Finally, (D) measures the CV as a percentage of variance (higher = greater change). Tree cover records the highest variance (~60%), followed by grassland (~50%), reflecting significant temporal fluctuations.

7.6 Matrix Of Annual Variations (Km2)

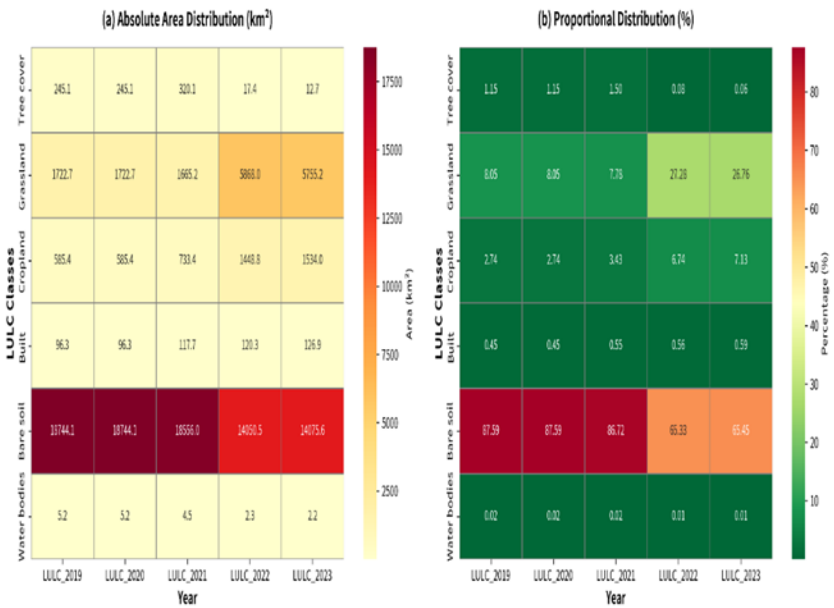

Figure 7. Matrix of annual variations (km2)

Figure 7 presents an analysis of land use and land cover (LULC) distribution from 2019 to 2023. The figure is divided into two components: (a) the distribution of absolute area in square kilometers (km²), shown using a heatmap gradient ranging from red (high values) to yellow (low values).

Component (b) illustrates the percentage (%) distribution using a color gradient that ranges from dark green (low values) to red (high values).The six categories are: Tree cover, Grassland, Cropland, Built-up areas, Bare soil, and Water bodies. The chart illustrates relative stability in the initial years, succeeded by substantial changes in 2022–2023, with bare soil initially prevailing and progressively diminishing.

In part (a), the areas remained stable from 2019 to 2021, followed by substantial alterations in 2022: a notable increase in grassland (from 1,665.2 km² to 5,968.0 km²) and cropland (from 733.4 km² to 1,448.8 km²), contrasted by a significant decline in bare soil (from 18,556.0 km² to 14,050.5 km²) and tree cover (from 320.1 km² to 17.4 km²). In 2023, projections indicate a continued modest drop in grassland and bare soil. Developed regions and aquatic environments are comparatively little, measuring under 130 km² and 5 km², respectively.

In part (b), the percentages indicate the following changes: bare soil declines from 87.59% in 2019 to 65.45% in 2023; grassland rises from 8.05% to 26.76%; and cropland increases from 2.74% to 7.13%. Tree cover diminishes from 1.15% to 0.06%, while built-up areas and water bodies persist below 0.6% and 0.02%, respectively.

7.7 Temporal Evolution Of LULC and Bare Soil

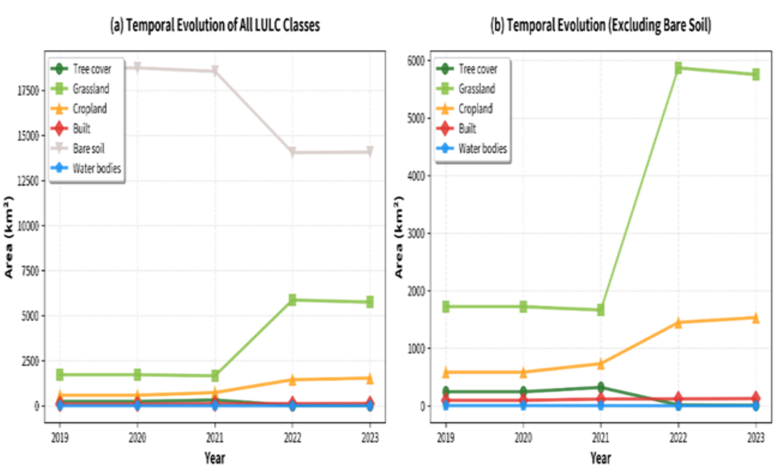

Figure 8. Temporal evolution of LULC and bare soil

The (figure 8) illustrates a temporal analysis of the progression of Land Use/Land Cover (LULC) categories from 2019 to 2023, segmented into two sections: (A) the temporal evolution of all categories, including bare soil (depicted in gray), which predominates the scale, and (B) the evolution excluding bare soil to emphasize the remaining categories. The primary categories consist of: tree cover (green), grassland (orange), cropland (red), built-up regions (blue), and water bodies (light blue). A line chart illustrates the areas in square kilometers (km^2) across the years.

In portion (A), bare soil has clear predominance, commencing at approximately 17,500 km^2 in 2019 and progressively diminishing to roughly 12,500 km^2 by 2023, with a notable decline occurring in 2022. Grassland initially measures approximately 250 km^2, then undergoes a significant increase in 2022 to about 5,000 km^2, subsequently stabilizing. Cropland is generally steady at approximately 500 km^2, with a minor increase observed in 2022. Tree cover increases marginally from approximately 250 km^2 to over 300 km^2 in 2021, subsequently declining to approximately 0 km^2 by 2023. Developed regions and aquatic environments are minimal (under 100 km^2) and very stable.

Part (B) emphasizes the alterations in categories excluding bare soil: a significant escalation in grassland from approximately 250 km^2 to almost 5,000 km^2 in 2022, succeeded by a marginal decline. Cropland increased little in 2022 (about 750 km^2), although tree cover and urban areas experienced a slow decline. This depiction highlights the swift changes in 2021–2022, aligning with prior research on semi-arid locations.

8. DISCUSSION

Research demonstrates the variety of applications and difficulties in overseeing semi-arid agricultural regions worldwide. The Aurangabad district in Maharashtra, India, is a significant semi-arid region particularly susceptible to climate change, marked by minimal summer monsoon precipitation, a low water table, and water-scarce agricultural practices (Roy & Inamdar, 2019). This region has overexploitation of natural resources due to fast industrialization and rising demographic pressure, resulting in a significant resource management challenge characterized by diminishing agricultural land and expanding degraded land (Roy & Inamdar, 2019).

Semi-arid regions in Kenya endure a highly variable environment characterized by drought and erratic rainfall patterns, with the ramifications of climate change on agricultural and livestock productivity exerting intricate consequences on food security that necessitate local parametrization (Obwocha et al., 2022). The application of the NDVI index to evaluate spatial and temporal differences in vegetation is crucial for demonstrating vegetation-climate feedback mechanisms at various stages of crop development (Obwocha et al., 2022). The irrigated perimeter of Tadla in Morocco serves as a significant case study, exemplifying one of the most diverse and fragmented agricultural regions in the nation, contributing to the national output of sugar beet, cereals, olives, citrus fruits, and pomegranates (Imanni et al., 2022). This region exemplifies the difficulties of crop mapping during climate change, with Morocco identified as one of the nations most impacted by this phenomenon (Imanni et al., 2022).

Numerous case studies in sub-Saharan Africa illustrate the relevance of remote sensing technologies. In Sudan, the application of the Sentinel-2 image collection within Google Earth Engine, utilizing SVM and Random Forest classifiers, facilitates the mapping of crop types in arid regions, offering essential insights for farmers and policymakers in land use planning and resource management (Altoom et al., 2025). In Nigeria, alterations in land use and cover significantly impact agricultural output in semi-arid regions, resulting in population migrations predominantly from rural areas (Eze, 2023). Algeria serves as a compelling example study, particularly in the regions of Biskra and Khenchela, where the amalgamation of Sentinel-1 radar data and Landsat 8 optical images enhances the categorization of various crop kinds and the observation of vegetation dynamics (Mayouf et al., 2024). In semi-arid Tunisia, where agricultural production is constrained by water scarcity and soil degradation, a novel methodology employing Google Earth Engine to analyze land cover through Landsat imagery and vegetation indices offers efficient strategies for examining the sustainable management of natural resources (Kadri et al., 2023).

South Africa exemplifies advanced methodological integration in the Northwest Province, utilizing an innovative approach that amalgamates the water ratio index, the normalized difference chlorophyll index, land cover mapping, and Cellular Automata-Markov modeling with temperature variations to monitor the dynamics of irrigated lands (Ali et al., 2025). This multi-model fusion integrates biophysical water availability, vegetation health, and prospective irrigation scenarios (Ali et al., 2025). Eastern Nusa Tenggara in Indonesia serves as a case study in Southeast Asia, examining alterations in land cover and land management concerning food security and environmental services, utilizing machine learning methodologies via Google Earth Engine (Ngongo et al., 2023). Central Asia is confronting desertification issues observed through remote sensing, with research emphasizing the effects of climate change, unsustainable land management methods, and population increase (Aslanov et al., 2023). These case studies demonstrate prevalent trends in semi-arid locations, notably substantial agricultural expansion resulting from the transformation of non-arable lands, shown by India's agricultural area, which grew by roughly 98% from 1991 to 2016 (Duraisamy et al., 2018). Effective management of irrigated regions in Morocco necessitates a comprehensive understanding of the spatiotemporal dynamics of agricultural systems, especially for cereals, which constitute 75% of the cultivated land (Benabdelouahab et al., 2018).

CONCLUSION

The empirical findings from 2019 to 2023 in Biskra clearly demonstrate a significant and dynamic transformation in land use patterns, marked by numerous noteworthy phenomena: There has been a notable increase in agricultural land and tree cover, driven by land reclamation efforts and enhanced agricultural practices, particularly in the cultivation of economically important crops such as palm trees, olives, and various essential vegetables for local sustenance and economy. Secondly, this agricultural expansion coincides with swift urbanization, occurring alongside economic growth and population increase, indicating a symbiotic relationship between urban development and agricultural productivity that mirrors the region's evolving demographics and economic demands.

Moreover, it is crucial to acknowledge the alarming reduction in pasture availability and the degradation of water bodies, which starkly demonstrates the intrinsic vulnerability of the region's natural resources, a condition intensified by the combined effects of climate change and the extensive exploitation of these resources through human activities. The ongoing presence of bare soil, despite the gradual exploitation of specific parts, highlights the environmental vulnerabilities that jeopardize the ecological equilibrium in the area.

Given these substantial transformations, it is crucial to acknowledge that they embody a complex interaction of opportunities and challenges; while these developments enhance Biskra's strategic role as a key agricultural center within the wider economic framework, they concurrently raise significant concerns about the sustainability of essential natural resources, particularly regarding the preservation of water and soil.

Therefore, the necessity to attain a careful equilibrium between agricultural expansion and essential environmental considerations becomes a crucial requirement for achieving sustainable development in this arid desert region, where modernization pressures must be reconciled with the need for ecological preservation. Therefore, a holistic strategy that combines agricultural development with sustainable practices is crucial for securing the long-term sustainability of Biskra's natural resources and promoting economic success. The findings from Biskra underscore a pivotal moment for strategic judgments to adeptly manage the conflicting trajectories of progress and preservation. Consequently, the future of this region depends on our collective capacity to enact policies that emphasize agricultural efficiency and environmental sustainability amid forthcoming challenges.

REFERENCES

Abdennour, M. A., Douaoui, A., Bradaï, A., Bennacer, A., & Fernández, M. P. (2019). Application of kriging techniques for assessing the salinity of irrigated soils : The case of El Ghrous perimeter, Biskra, Algeria. Spanish Journal of Soil Science.

Abdivaitov, K., & Strobl, J. (2023). Agricultural Land Use Dynamics—A Case Study of Kumkurgan District, Uzbekistan. International Journal of Geoinformatics.

Abubakar, G. A., Wang, K., Koko, A. F., Husseini, M. I., Shuka, K. A. M., Deng, J., & Gan, M. (2023). Mapping Maize Cropland and Land Cover in Semi-Arid Region in Northern Nigeria Using Machine Learning and Google Earth Engine. Remote Sensing.

Agadi, R., Sakhraoui, K., Hirschhausen, C. von, & Kebir, N. (2023). Sustainable Farming through Decentralized Energy Systems : Opportunities and barriers. E3S Web of Conferences.

Ali, A., Baloch, M. Y. J., Naveed, M., Nigar, A., Almalki, A. S., Rasool, A., Gedfew, M. A., & Arafat, A. A. (2025). Advanced satellite-based remote sensing and data analytics for precision water resource management and agricultural optimization. Scientific Reports.

Alkhalil, A., Kadaouré, I., & Kouadio, M. (2020). An Evaluation of 20-m ESA-CCI S2 Prototype LC Product. Frontiers in Sustainable Food Systems.

Altoom, M. B., Adam, E., & Jackson, C. M. (2025). Mapping cropland types in heterogeneous arid environments using machine learning algorithms and dataset variations on Google Earth Engine. Journal of Aridland Agriculture.

Amazirh, A., Bouras, E., Olivera-Guerra, L., Er-raki, S., & Chehbouni, A. (2021). Retrieving Crop Albedo Based on Radar Sentinel-1 and Random Forest Approach. Remote Sensing.

Ariom, T. O., Dimon, E., Nambeye, E., Diouf, N. S., Adelusi, O. O., & Boudalia, S. (2022). Climate-Smart Agriculture in African Countries : A Review of Strategies and Impacts on Smallholder Farmers. Sustainability.

Aslanov, I., Teshaev, N., Khayitov, K., Mukhtorov, U., Khaitbaeva, J., & Murodova, D. (2023). Analysis of desertification trends in Central Asia based on MODIS Data using Google Earth Engine. E3S Web of Conferences.

Baade, J., Schmullius, C., Urban, M., Kunstmann, H., Laux, P., Zhang, Z., Glotzbach, C., Gessner, U., Hirner, A., Kluter, P., Otte, I., Aucamp, I., Chirima, G., Elbasit, M. A., Morgenthal, T., Smit, I., Strydom, T., Roux, J. le, Maltitz, G. V., & Msibe, T. (2021). South African Land Degradation Monitor (SALDI) – An overview of recent advancements.

Balasubramani, K. (2020). Assessment Of Watershed Resources For Sustaınable Agrıcultural Development: A Case Of Developıng An Operatıonal Methodology Under Indıan Condıtıons Through Geospatıal Technologıes.

Begizew, G. (2021). Agricultural production system in arid and semi-arid regions. International Journal of Agricultural Science and Food Technology.

Belhadj, A., Allache, F. D., Boulghobra, N., & Mebrek, N. (2023). Botanical Diversity of Arid Steppe in South East of Algeria (Biskra). Journal of Ecological Engineering.

Benabdelouahab, T., Derauw, D., Lionboui, H., Hadria, R., Tychon, B., Boudhar, A., Balaghi, R., Lebrini, Y., Maaroufi, H., & Barbier, C. (2018). Using SAR Data to Detect Wheat Irrigation Supply in an Irrigated Semi-arid Area. Journal of Agricultural Sciences.

Benamor, K., & Benabbas, M. (2019). Effect of Street Morphology on Buildings' Thermal Storage in a Hot and Arid Climate : Case Study of Biskra (Algeria). Journal of Building Materials and Structures.

Bendjedidi, S., Bada, Y., & Meziani, R. (2019). Urban plaza design process using space syntax analysis: International Review for Spatial Planning and Sustainable Development.

Bengouga, K., LahmadiSalwa, L., Zeguerou, R., Maaoui, M., & Halis, Y. (2019). Livestock in rural piedmont regions of Algeria. Biotehnologija u stocarstvu.

Berkouk, D., Bouzir, T., Maffei, L., & Masullo, M. (2020). Examining the Associations between Oases Soundscape Components and Walking Speed : Correlation or Causation? Sustainability.

Besbas, S., Nocera, F., Zemmouri, N., Khadraoui, M. A., & Besbas, A. (2022). Parametric-based multi-objective optimization workflow : Daylight and energy performance study of hospital building in Algeria. Sustainability, 14(19), 12652.

Bouchemal, S. (2021). A note on the dynamics of food systems in Algeria : The example of the Ziban and the Souf.

Boumessenegh, amel, & Dridi, H. (2021). Determination of the flood volume by the aspects of peak flow and flood hydrograph at the level of the city of Biskra, Wadi Biskra watershed, Algeria.

Degui, N., Djili, K., Daoud, Y., & Belghemmaz, S. (2024). Speciation of Zn in Arid Soils With Saline Accumulations. Case Study of the Biskra Region, Algeria. Revısta Terra Latınoamerıcana.

Desta, Y., Haile, M., Gebresamuel, G., & Sibhatleab, M. (2020). Potential, quality and quantity assessment of sesame plant residue in dry land vertisols of Tigrai, Ethiopia; Approach for sustainability of dry-land farming. Heliyon.

Djelloul, G., & Djamel-Eddine, Z. (2012). Study of the wildlife acarology (Acari : Oribatida) in the palm groves of Biskra.

Duraisamy, V., Bendapudi, R., & Jadhav, A. (2018). Identifying hotspots in land use land cover change and the drivers in a semi-arid region of India. Environmental Monitoring & Assessment.

Eisfelder, C., Boemke, B., Gessner, U., Sogno, P., Alemu, G., Hailu, R., Mesmer, C., & Huth, J. (2024). Cropland and Crop Type Classification with Sentinel-1 and Sentinel-2 Time Series Using Google Earth Engine for Agricultural Monitoring in Ethiopia. Remote Sensing.

Eze, J. (2023). Impact of Land use and land cover change on Agricultural Productivity in Semi-Arid Region of Nigeria. BADEGGI JOURNAL OF AGRICULTURAL RESEARCH AND ENVIRONMENT.

Feng, S., & Fu, Q. (2013). Expansion of global drylands under a warming climate.

Ganjirad, M., & Bagheri, H. (2024a). Google Earth Engine-based mapping of land use and land cover for weather forecast models using Landsat 8 imagery. Ecological Informatics, 80, 102498. https://doi.org/10.1016/j.ecoinf.2024.102498

Ganjirad, M., & Bagheri, H. (2024b). Google Earth Engine-based mapping of land use and land cover for weather forecast models using Landsat 8 imagery. Ecological Informatics, 80, 102498. https://doi.org/10.1016/j.ecoinf.2024.102498

Ganjirad, M., & Bagheri, H. (2024c). Google Earth Engine-based mapping of land use and land cover for weather forecast models using Landsat 8 imagery. Ecological Informatics, 80, 102498. https://doi.org/10.1016/j.ecoinf.2024.102498

Goldblatt, R., Ballesteros, A. R., & Burney, J. (2017). High Spatial Resolution Visual Band Imagery Outperforms Medium Resolution Spectral Imagery for Ecosystem Assessment in the Semi-Arid Brazilian Sertão. Remote Sensing.

Hafyani, M. E., Essahlaoui, A., Fung-Loy, K., Hubbart, J., & Rompaey, A. van. (2021). Assessment of Agricultural Water Requirements for Semi-Arid Areas : A Case Study of the Boufakrane River Watershed (Morocco). Applied Sciences.

Hemidi, W., & Laamari, M. (2020). Aphid's parasitoid fauna and their trophic associations in the oasis ecosystems of Zibans (Biskra, Algeria).

Homrani, M., Escuredo, O., Rodríguez-Flores, M., Fatiha, D., Mohammed, B., Homrani, A., & Seijo, M. (2020). Botanical Origin, Pollen Profile, and Physicochemical Properties of Algerian Honey from Different Bioclimatic Areas. Foods.

Htitiou, A., Boudhar, A., Lebrini, Y., Hadria, R., Lionboui, H., & Benabdelouahab, T. (2020). A comparative analysis of different phenological information retrieved from Sentinel-2 time series images to improve crop classification : A machine learning approach. Geocarto International.

Husein, H. H., Lucke, B., Bäumler, R., & Sahwan, W. (2021). A Contribution to Soil Fertility Assessment for Arid and Semi-Arid Lands. Soil Systems.

Imanni, H. S. E., Harti, A., Hssaisoune, M., Velástegui-Montoya, A., Elbouzidi, A., Addi, M., Iysaouy, L. E., & Hachimi, J. E. (2022). Rapid and Automated Approach for Early Crop Mapping Using Sentinel-1 and Sentinel-2 on Google Earth Engine; A Case of a Highly Heterogeneous and Fragmented Agricultural Region. Journal of Imaging.

Ioannidou, M., Koukos, A., Sitokonstantinou, V., Papoutsis, I., & Kontoes, C. (2022). Assessing the Added Value of Sentinel-1 PolSAR Data for Crop Classification. Remote Sensing.

Kadri, N., Jebari, S., Augusseau, X., Mahdhi, N., Lestrelin, G., & Berndtsson, R. (2023). Analysis of Four Decades of Land Use and Land Cover Change in Semiarid Tunisia Using Google Earth Engine. Remote Sensing.

Karnieli, A., French, A., Bounoua, L., Ben-Gal, A., & Imhoff, M. (2012). Evaluating and predicting water consumption by irrigated agriculture in the semi-arid regions of Israel and the U.S. : Inverse biophysical modeling utilizing spaceborne imagery.

Kganyago, M., Ovakoglou, G., Mhangara, P., Alexandridis, T., Odindi, J., Adjorlolo, C., & Mashiyi, N. (2020). Validation of atmospheric correction approaches for Sentinel-2 under partly-cloudy conditions in an African agricultural landscape. Remote Sensing.

Kobayashi, N., Tani, H., Wang, X., & Sonobe, R. (2019). Crop classification using spectral indices derived from Sentinel-2A imagery. Journal of Information and Telecommunication.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World Map of the Köppen-Geiger climate classification updated.

Kouider, D. B., Athmani, H., & Bensefia, S. (2025). Reuse of agricultural drainage water and wastewater for crop irrigation in southeastern Algeria. Open Geosciences.

Kuper, M., Faysse, N., Hammani, A., Hartani, T., Marlet, S., Hamamouche, M. F., & Ameur, F. (2016). Liberation or anarchy ? The Janus nature of groundwater use on North Africa's new irrigation frontiers.

Lahmar, I., Zemmouri, N., Cannavale, A., & Martellotta, F. (2019). Investigating the impact of electrochromic glazing on energy performance in hot arid climate using parametric design. IOP Conference Series: Materials Science and Engineering.

Laouar, S., Boumaraf, B., & Saadi, I. (2023). Morpho-Pedology Varıatıons In A Pre-Saharan Regıon Case Zıban Soıls. Analele Universităţii din Oradea: Seria Geografie.

Lebrini, Y., Boudhar, A., Laamrani, A., Htitiou, A., Lionboui, H., Salhi, A., Chehbouni, A., & Benabdelouahab, T. (2021). Mapping and Characterization of Phenological Changes over Various Farming Systems in an Arid and Semi-Arid Region Using Multitemporal Moderate Spatial Resolution Data. Remote Sensing.

Li, L., Friedl, M., Xin, Q., Gray, J., Pan, Y., & Frolking, S. (2014). Mapping Crop Cycles in China Using MODIS-EVI Time Series. Remote Sensing.

Mayouf, R., Hanafi, M. T., & Mostefaoui, O. (2024). Machine learning-based crop type detection and vegetation mon-itoring using Sentinel-1 SAR and Landsat 8. South Florida Journal of Development.

Meng, Z., Dang, X., & Gao, Y. (2019). Land Degradation. Public Private Partnership for Desertification Control in Inner Mongolia.

Miloudi, A., & Remini, B. (2018). The Ghout of Souf : An Original Hydroagricultural System. GeoScience Engineering.

Mohammed, T., Gherissi, D., Moussa, C., & Hanane, M. (2023). Influence of Region on Some Reproductive Parameters in Ouled Djellal Sheep. Jurnal Ilmu Ternak dan Veteriner.

Moraes, D., Campagnolo, M. L., & Caetano, M. (2024a). Training data in satellite image classification for land cover mapping : A review. European Journal of Remote Sensing, 57(1), 2341414. https://doi.org/10.1080/22797254.2024.2341414

Moraes, D., Campagnolo, M. L., & Caetano, M. (2024b). Training data in satellite image classification for land cover mapping: A review. European Journal of Remote Sensing, 57(1), 2341414. https://doi.org/10.1080/22797254.2024.2341414

Nafissa, S., Mohammed, B., Y, U. A., Nageshvar, P., Laura, C., Alessandra, C., & Khaoula, T. (2020). Environmental risk assessment of pesticide use in Algerian agriculture. Journal of Applied Biology & Biotechnology.

Nasiri, V., Deljouei, A., Moradi, F., Sadeghi, S. M. M., & Borz, S. A. (2022). Land Use and Land Cover Mapping Using Sentinel-2, Landsat-8 Satellite Images, and Google Earth Engine: A Comparison of Two Composition Methods. Remote Sensing, 14(9), 1977. https://doi.org/10.3390/rs14091977

Ngongo, Y., deRosari, B., Basuki, T., Njurumana, G. N., Nugraha, Y., Harianja, A. H., Ardha, M., Kustiyo, K., Shofiyati, R., Heryanto, R. B., Rawung, J. B., Sondakh, J., Senewe, R. E., daSilva, H., Hutapea, R., Mattitaputty, P. R., Kenduballa, Y. P., Kotta, N., Seran, Y. L., … Nugroho, H. Y. (2023). Land Cover Change and Food Security in Central Sumba: Challenges and Opportunities in the Decentralization Era in Indonesia. Land.

Nicolau, A. P., Dyson, K., Saah, D., & Clinton, N. (2024). Accuracy Assessment: Quantifying Classification Quality. In J. A. Cardille, M. A. Crowley, D. Saah, & N. E. Clinton (Éds.), Cloud-Based Remote Sensing with Google Earth Engine: Fundamentals and Applications (p. 135-145). Springer International Publishing. https://doi.org/10.1007/978-3-031-26588-4_7

Obwocha, E. B., Ramisch, J., Duguma, L., & Orero, L. (2022). The Relationship between Climate Change, Variability, and Food Security: Understanding the Impacts and Building Resilient Food Systems in West Pokot County, Kenya. Sustainability.

Oukil, A., Nourani, A., Soltani, A., Boulassel, M., & Bencheikh, A. (2023). Improving agricultural sustainability through farm mergers: An energy efficiency perspective. International Journal of Agricultural Sustainability.

Pareeth, S., Karimi, P., Shafiei, M., & Fraiture, C. (2019). Mapping Agricultural Landuse Patterns from Time Series of Landsat 8 Using Random Forest Based Hierarchial Approach. Remote Sensing.

Rais, M., Boumerzoug, A., & Baranyai, B. (2021). Energy performance diagnosis for the residential building façade in Algeria. Pollack Periodica.

Rais, M., Boumerzoug, A., Halada, M., & Sriti, L. (2019). Optimizing the cooling energy consumption by the passive traditional façade strategies in hot dry climate. Pollack Periodica, 14(1), 177-188.

Remelgado, R., Zaitov, S., Kenjabaev, S., Stulina, G., Sultanov, M., Ibrakhimov, M., Akhmedov, M., Dukhovny, V., & Conrad, C. (2020). A crop type dataset for consistent land cover classification in Central Asia. Scientific Data.

Roy, A., & Inamdar, A. (2019). Multi-temporal Land Use Land Cover (LULC) change analysis of a dry semi-arid river basin in western India following a robust multi-sensor satellite image calibration strategy. Heliyon.

Saadi, H., Debabèche, M., & Traoré, F. (2020). Groundwater Management For Irrıgated Agrıculture In South-Eastern Algerıa By Approachıng Crop Water Needs. Analele Universităţii din Oradea: Seria Geografie.

Saker, A., & Akakba, A. (2024). Urban traffic incident management, using network analysis to improve the evacuation time to healthcare facilities. Geomatics, Landmanagement and Landscape.

Samasse, K., Hanan, N., Tappan, G., & Diallo, Y. (2018). Assessing Cropland Area in West Africa for Agricultural Yield Analysis. Remote Sensing.

Selmane, S. (2015). Dynamic relationship between climate factors and the incidence of cutaneous leishmaniasis in Biskra Province in Algeria. Annals of Saudi Medicine.

Selmane, S., & L'Hadj, M. (2016). Forecasting and prediction of scorpion sting cases in Biskra province, Algeria, using a seasonal autoregressive integrated moving average model. Epidemiology and Health, 38, e2016044. https://doi.org/10.4178/epih.e2016044

Trivedi, M. B., Marshall, M., Estes, L., Bie, C. D. D., Chang, L., & Nelson, A. (2023). Cropland Mapping in Tropical Smallholder Systems with Seasonally Stratified Sentinel-1 and Sentinel-2 Spectral and Textural Features. Remote Sensing.

Wood, S. J., Jones, D., & Moore, R. (2000). Accuracy of rainfall measurement for scales of hydrological interest.

Zohra, N., Houria, B., AbdeLdjabar, N., & Messaoud, S. (2024). Statıstıcal Characterızatıon Of Groundwater Qualıty In The Bıskra Regıon, Northeastern Algerıa. International Journal of Innovative Technologies in Social Science.

CHAPTER 2
AGRI-ECOSYSTEM MODELING: DYNAMIC SIMULATIONS FOR POLICY AND PRACTICE

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INTRODUCTION

Agricultural systems operate as complex, adaptive ecosystems in which biophysical processes, management practices, socio-economic drivers, and policy interventions interact across multiple spatial and temporal scales. Crop growth, soil nutrient cycling, water dynamics, land-use decisions, and farmer behavior are tightly coupled and continuously influenced by external pressures such as climate variability, market dynamics, population growth, and environmental regulation (Jones et al., 2017; Van Ittersum et al., 2013). Understanding and managing these interdependencies has become increasingly critical as global agriculture faces mounting challenges related to climate change, food insecurity, land degradation, and the need for sustainable intensification.

In this context, agri-ecosystem modeling has emerged as a key scientific and decision-support approach for analyzing agricultural system behavior and supporting evidence-based policy formulation. Agri-ecosystem models are computational representations that integrate empirical data and theoretical knowledge to simulate interactions among crops, soils, climate, management practices, and human decision-making processes (Jun, 2023; Wallach et al., 2016). These models enable researchers and policymakers to explore alternative management and policy scenarios, forecast system responses under uncertainty, and evaluate trade-offs among productivity, environmental sustainability, and socio-economic outcomes.

Dynamic simulation is central to agri-ecosystem modeling because agricultural processes are inherently time-dependent. Crop phenology, soil carbon dynamics, nutrient cycling, land-use transitions, and technology adoption evolve over seasons, years, and decades, often exhibiting nonlinear behavior and delayed feedbacks (Confalonieri et al., 2016). Static or snapshot analyses are therefore insufficient for capturing long-term system trajectories and cumulative impacts. Dynamic models allow stakeholders to assess how short-term decisions influence long-term outcomes, such as yield stability, greenhouse gas emissions, soil health, and system resilience under changing climatic and socio-economic conditions (Rosenzweig et al., 2014). A wide range of agri-ecosystem modeling approaches has been developed to address diverse research and policy objectives.

Process-based crop models, such as APSIM and DSSAT, simulate physiological and environmental processes governing crop growth and yield formation in response to climate and management inputs (Jones et al., 2017). Land-use and spatial models capture patterns of land conversion and landscape change driven by biophysical constraints and socio-economic pressures (Verburg & Overmars, 2007). Biogeochemical models focus on nutrient and carbon cycling, enabling quantification of greenhouse gas emissions and soil organic carbon dynamics relevant to climate mitigation policy (DayCent, 2025). More recently, agent-based and socio-technical models have been developed to explicitly represent farmer decision-making, social interactions, and technology adoption processes (Berger & Troost, 2014; Schlüter et al., 2017), while system dynamics models provide high-level insights into feedbacks among environmental, economic, and policy subsystems over long time horizons.

Beyond advancing scientific understanding, agri-ecosystem models play an increasingly important role in policy evaluation and decision support. Scenario-based simulations are widely used to assess climate change impacts on agricultural productivity, evaluate mitigation and adaptation strategies, and examine the potential consequences of alternative policy interventions before implementation (Rosenzweig et al., 2014; Pielke, 2007). By comparing baseline and policy-driven scenarios, these models help identify trade-offs, synergies, and unintended consequences associated with agricultural and environmental policies (Ascough et al., 2008).

Despite their growing relevance, agri-ecosystem models face important challenges related to data availability, model complexity, uncertainty, representation of human behavior, and the translation of scientific outputs into actionable policy guidance (Confalonieri et al., 2016; Jones et al., 2017). Addressing these limitations requires improved data infrastructures, transparent calibration and validation procedures, interdisciplinary modeling approaches, and stronger science–policy interfaces. Against this backdrop, this chapter provides a comprehensive overview of agri-ecosystem modeling with a focus on dynamic simulations for policy and practice.

It reviews the foundational principles and evolution of agri-ecosystem models, examines major modeling approaches and their applications, and discusses data requirements, calibration, and validation. The chapter further explores practical applications in climate change assessment, land-use planning, and policy analysis, highlights key challenges and limitations, and outlines emerging directions, including the integration of remote sensing, big data, and hybrid socio-biophysical modeling frameworks. Through this synthesis, the chapter emphasizes the growing importance of agri-ecosystem models as essential tools for designing resilient, sustainable, and evidence-based agricultural policies.

1. FOUNDATIONS OF AGRI-ECOSYSTEM MODELING

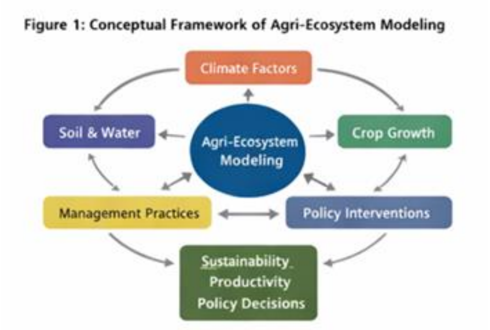

Figure 1. Conceptual Framework of Agri-Ecosystem Modeling

Agri-ecosystem models are essentially computational representations of real-world agricultural systems that use mathematical equations to capture interactions between system components (Jun, 2023). These interactions include crop growth, soil nutrient cycling, water balance, and responses to management decisions (Jun, 2023). Historically, agricultural models began with simple representations of crop growth and later evolved to integrate more complex environmental and socio-economic factors (American University of Beirut, 2025). Models differ based on their temporal and spatial scales, level of biological detail, and the types of processes they represent. Temporal resolution can range from daily to annual time steps, while spatial resolution may span field scale to continental landscapes (Nature Research Intelligence, 2025).

The choice of model structure depends on research goals: for instance, a land-use change model like CLUE simulates spatial patterns of land-use conversion, whereas biogeochemical models like DayCent simulate nutrient and carbon fluxes in agroecosystems. It shows in Figure 1.

2. TYPES OF AGRI-ECOSYSTEM MODELS

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3. TYPES OF AGRI-ECOSYSTEM MODELS

Agri-ecosystem models are diverse computational tools designed to represent the complex interactions within agricultural systems. They vary in scope, scale, and level of detail, depending on the specific research or policy question being addressed. Each type of model provides unique insights, enabling researchers and policymakers to explore scenarios, assess trade-offs, and design strategies for sustainable, productive, and resilient agricultural systems.

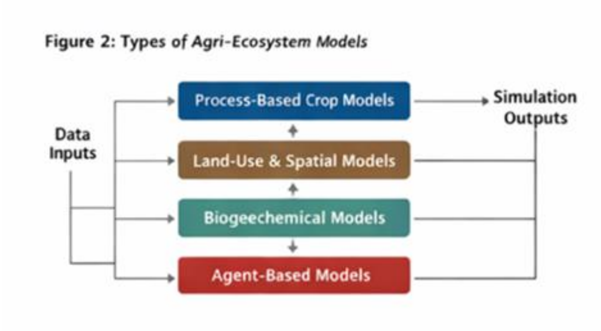

Figure 2. Types of Agri-Ecosystem Models

3.1 Process-Based Crop Models

Process-based models simulate physiological and environmental processes that drive crop development and yield formation. Examples include APSIM (Agricultural Production Systems Simulator) and DSSAT (Decision Support System for Agrotechnology Transfer), which integrate weather, soil, and management data to forecast crop outcomes (American University of Beirut, 2025; Nature Research Intelligence, 2025). These models are widely used to evaluate responses to climate variability, irrigation strategies, and genetic improvements.

Such models often include mechanistic equations representing photosynthesis, respiration, and energy balance. For example, CropSyst integrates processes governing soil moisture, nutrient cycling, and plant growth to support sustainable management decisions under variable climates (ACS ES&T Engineering, 2021). These simulations allow researchers to explore hypothetical scenarios and assess how changes in climate or management practices might influence crop performance and resource use (ACS ES&T Engineering, 2021).

3.2 Dynamic Land Use and Spatial Models

Models like CLUE (Conversion of Land Use and its Effects) and PLUS (Patch-Generating Land Use Simulation) aim to simulate changes in land use and land cover driven by socio-economic and environmental factors.

CLUE models combine biophysical and human drivers to allocate land uses spatially across a landscape, while PLUS incorporates cellular automata approaches to simulate complex spatial patterns of land expansion.

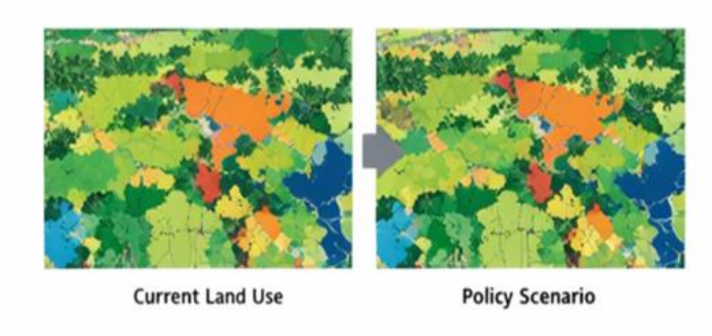

Figure 4. Land Use Change Scenarios

Dynamic land use models are particularly valuable for understanding how policy interventions such as incentives for conservation agriculture or zoning regulations affect land-use patterns over long time horizons. By simulating land conversion under various scenarios, stakeholders can evaluate trade-offs between agriculture, urban growth, and natural ecosystems.

3.3 Biogeochemical and Ecosystem Process Models

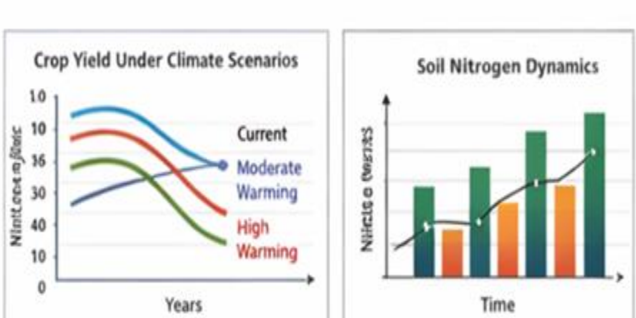

Figure 5. Example of Dynamic Simulation Outputs

Biogeochemical models like DayCent simulate daily fluxes of carbon and nitrogen among soil, vegetation, and the atmosphere. These models are essential for quantifying greenhouse gas emissions and nutrient leaching from cropland, providing insights relevant to climate policy and environmental regulation. For instance, DayCent outputs include daily N_2O emissions and soil organic carbon changes, which inform inventories used by policymakers to design mitigation strategies.

Such models often require high-resolution input data, including climate records, soil properties, and management practices. Their outputs provide quantitative estimates of ecological responses over time, which can be used to evaluate the environmental performance of different farming practices and policies.

3.4 Agent-Based and Socio-Technical Models

Emerging models integrate social behavior and decision-making processes into ecosystem simulations. For example, AdoptAgriSim is a socio-technical agent-based model that simulates the adoption of smart agricultural technologies by farmers across diverse regions using reinforcement learning and network interaction structures (Nature, 2025). This model illustrates how economic, social, and technological factors interplay to shape adoption dynamics insights that are difficult to capture with purely process-based models.

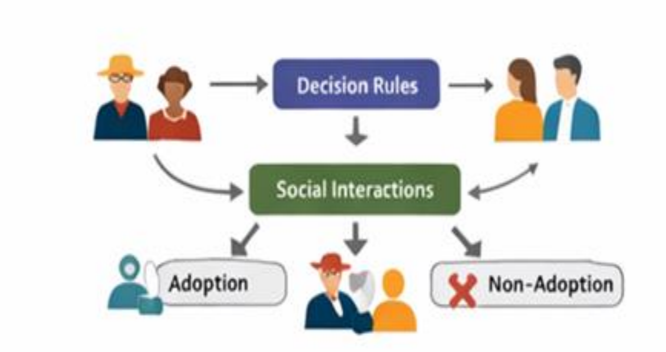

Figure 6. Agent-Based Model of Technology Adoption

These agent-based approaches are particularly useful when exploring behavioral responses to policy incentives, peer influence, and market pressures. By capturing how farmers make decisions based on individual preferences and social interactions, these models provide nuanced forecasts of technology diffusion and its implications for agricultural productivity and sustainability.

3.5 System Dynamics Models

System dynamics (SD) models represent agricultural systems at a high level of abstraction by emphasizing stocks, flows, feedback loops, and time delays that govern system behavior over long time horizons. Unlike detailed process-based or spatially explicit models, system dynamics approaches focus on understanding the structural causes of system behavior, making them particularly suitable for analyzing complex interactions among agricultural production, resource use, economic performance, and environmental outcomes (Wallach et al., 2016).

In agri-ecosystem modeling, SD models are widely used to examine how policies, management strategies, and external drivers influence long-term system trajectories. Key components such as crop production, water use, nutrient inputs, emissions, and economic returns are represented as interconnected subsystems, allowing researchers to explore feedback mechanisms and unintended consequences that may not be evident in static or short-term analyses. For example, a system dynamics framework applied to the eco-agriculture system in China simulated interactions among agricultural production, resource consumption, and environmental impacts under different policy scenarios, revealing trade-offs between economic growth, resource depletion, and environmental sustainability (ScienceDirect, 2012).

System dynamics models are particularly effective for policy evaluation and scenario analysis, as they enable stakeholders to compare alternative policy pathways such as subsidy structures, conservation measures, or intensification strategies and assess their cumulative impacts over decades. By simulating long-term outcomes, SD models help identify leverage points where small policy interventions can lead to substantial system-wide improvements, as well as potential risks associated with delayed or poorly coordinated actions (Pielke, 2007).

Another key strength of system dynamics modeling lies in its suitability for participatory and stakeholder-engaged modeling processes. Because SD models use conceptual representations and causal loop diagrams, they can be more accessible to policymakers, extension agents, and practitioners than highly technical mechanistic models. This transparency facilitates dialogue among stakeholders, improves shared understanding of system behavior, and enhances the credibility and usability of model-based policy recommendations (Ascough et al., 2008).

Despite their advantages, system dynamics models also have limitations. Their aggregated structure may oversimplify spatial heterogeneity and farm-level variability, and they often rely on generalized assumptions rather than detailed empirical parameterization. Consequently, SD models are most effective when used in combination with process-based, spatial, or agent-based models, forming integrated modeling frameworks that balance conceptual clarity with quantitative precision.

Overall, system dynamics models provide a valuable lens for examining the long-term dynamics of agricultural systems and for supporting strategic, policy-oriented decision-making. When integrated with empirical data, stakeholder input, and complementary modeling approaches, they offer powerful insights into the pathways toward sustainable and resilient agri-ecosystems.

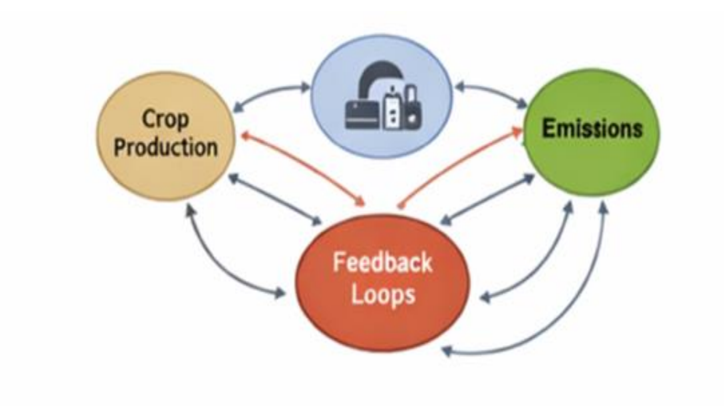

Figure 7. Agent-Based Model of Technology Adoption

Table 1. Comparison of Agri-Ecosystem Models

Model Type	Example Models	Key Features	Inputs	Outputs	Application
Process-Based Crop	APSIM, DSSAT	Physiological crop processes, mechanistic	Climate, soil, management	Yield, water use, N uptake	Climate adaptation, management evaluation
Land-Use / Spatial	CLUE, PLUS	Spatial land allocation, cellular automata	Socio-economic, environmental	Land cover projections	Policy evaluation, land planning
Biogeochemical	DayCent, Century	Nutrient & carbon cycles	Climate, soil, management	GHG emissions, SOC	Environmental sustainability, mitigation
Agent-Based	AdoptAgriSim	Farmer behavior, tech adoption	Socio-economic, network	Adoption rates, productivity	Policy incentives, technology diffusion
System Dynamics	Eco-Agriculture SD	Stocks, flows, feedback	Aggregated socio-ecological	Resource use, emissions	Long-term policy & sustainability analysis

4. MODEL INPUTS, OUTPUTS, AND CALIBRATION

Agri-ecosystem models share a core requirement: high-quality data. Inputs typically include climate records (temperature, precipitation), soil characteristics (texture, organic matter), crop parameters (phenology, growth rates), and management data (fertilization, irrigation). For socio-economic models, additional data such as market prices, demographics, and technology adoption rates may be needed.

Calibration and validation are critical for model credibility. Calibration aligns model outputs with observed data, while validation tests model performance on independent datasets. For example, models like APSIM and DayCent are calibrated using historical crop yield and gas flux measurements to ensure realistic representations of agroecosystem dynamics.

Outputs typically include crop yields, soil nutrient levels, greenhouse gas emissions, land use projections, and adoption rates of technologies under different scenarios. These outputs inform decision support systems and policy evaluations.

Table 2. Sample Model Inputs and Outputs

Parameter	Input Type	Unit	Example Value	Output
Temperature	Climate	°C	25	Effect on crop growth
Precipitation	Climate	mm/day	5	Soil moisture dynamics
Soil Organic Matter	Soil	%	2.5	Carbon sequestration
Fertilizer	Management	kg/ha	120	Crop N uptake, N_2O emission
Adoption Rate	Socio-economic	%	40	Technology diffusion

5. APPLICATIONS IN POLICY AND PRACTICE

5.1 Climate Change and Agricultural Resilience

Agri-ecosystem models are pivotal for assessing climate change impacts on agriculture and for designing adaptation strategies. For instance, simulations using APSIM suggest that conservation agriculture practices maintain protein yields under changing climate dynamics in northern Mozambique, highlighting their resilience benefits (Lalani et al., 2025). Such studies provide essential evidence for policymakers who must prioritize adaptation investments under budget constraints.

Dynamic models also help quantify future greenhouse gas emissions from soils and vegetation, which feed into national mitigation targets under frameworks like the United Nations Framework Convention on Climate Change (UNFCCC). By simulating emissions under alternative management practices, models like DayCent guide national policy decisions on fertilizer use, cover cropping, and conservation tillage.

5.2 Policy Evaluation and Scenario Analysis

Simulations support policy analysis by comparing outcomes under alternative scenarios. For example, models can estimate the long-term effects of subsidies for sustainable practices versus baseline scenarios, revealing potential environmental and economic benefits or trade-offs. System dynamics models have been used to recommend integrative policies in eco-agriculture systems by simulating outcomes through 2050 (ScienceDirect, 2012).

Land use models like CLUE inform land-use planning, allowing policymakers to evaluate how zoning changes, urban expansion pressures, or incentives for conservation agriculture might affect landscape dynamics. Such spatially explicit forecasts help balance competing priorities among food production, biodiversity, and ecosystem services. Similarly, socio-technical agent-based models like AdoptAgriSim inform technology diffusion policies by highlighting the roles of peer influence and economic incentives in adoption rates across regions. These insights help tailor interventions that accelerate beneficial innovation uptake.

Table 3. Illustrative Scenario Analysis Table

Scenario	Management Practice	Crop Yield Change (%)	N_2O Emission Change (%)	Policy Implication
Baseline	Current practices	0	0	Status quo
Conservation Agriculture	Reduced tillage + cover crops	+8	-12	Promote adoption via subsidies
High Fertilizer Input	Intensive fertilization	+15	+25	Risk of environmental degradation

6. CHALLENGES AND LIMITATIONS

Despite their growing utility in understanding agricultural systems, assessing climate change impacts, and supporting decision-making, agri-ecosystem models face a range of conceptual, technical, and practical challenges that limit their accuracy, transferability, and policy relevance.

These challenges arise from constraints in data availability and quality, increasing model complexity and associated uncertainties, difficulties in representing human behavior and socio-economic dynamics, and barriers in translating complex model outputs into actionable policy guidance. Furthermore, the scalability of models across spatial and temporal domains remains limited, particularly when transferring applications from data-rich regions to smallholder and resource-constrained systems.

While recent methodological advances and computational improvements offer promising avenues for addressing some of these issues, persistent limitations in calibration, validation, stakeholder interpretation, and interdisciplinary integration continue to affect the robustness and applicability of agri-ecosystem modeling frameworks. Collectively, these challenges underscore the need for improved data infrastructures, transparent uncertainty assessment, enhanced integration of human dimensions, and stronger science–policy interfaces to fully realize the potential of agri-ecosystem models for sustainable agricultural management and long-term policy planning.

6.1 Data Availability and Quality

The accuracy and reliability of agri-ecosystem models are highly dependent on the availability, consistency, and resolution of input data, including climatic variables, soil properties, crop parameters, and farm management information. However, in many regions—particularly in developing countries—such detailed and long-term datasets are limited or unavailable. Smallholder agricultural systems often lack continuous meteorological records, site-specific soil surveys, and systematic documentation of management practices such as planting dates, irrigation schedules, fertilizer application, and pest control strategies (Van Ittersum et al., 2013).

Moreover, available datasets frequently suffer from missing values, measurement errors, outdated information, or coarse spatial and temporal resolution, leading to increased uncertainty in model simulations (Liu et al., 2019).

Although advances in remote sensing technologies and global agricultural databases have improved data accessibility, these sources may not adequately capture local heterogeneity, farm-level variability, and fine-scale environmental conditions (Jones et al., 2017). Consequently, limitations in data availability and quality can constrain model calibration and validation, reduce predictive accuracy, and restrict the broader applicability of agri-ecosystem models across diverse agro-ecological and socio-economic contexts.

6.2 Model Complexity and Uncertainty

Agri-ecosystem models often involve complex representations of biophysical, chemical, and management processes, including crop growth, soil nutrient cycling, water dynamics, and climate interactions. While such complexity enables more realistic simulations of agricultural systems, it simultaneously increases the number of parameters and underlying assumptions, many of which are difficult to quantify with precision (Wallach et al., 2016). Uncertainties associated with model structure, parameterization, and input data can propagate through the modeling framework, resulting in substantial variability in simulation outcomes (Confalonieri et al., 2016). Moreover, interactions among multiple subsystems are not always fully understood or adequately represented, particularly under changing climatic conditions and evolving management practices (Jones et al., 2017).

Model calibration and validation are further constrained by limited and spatially sparse field observations, especially when models are applied at regional or national scales (Van Ittersum et al., 2013). Consequently, uncertainty in model outputs may reduce stakeholder confidence and complicate the interpretation of results for decision-making and policy formulation, underscoring the importance of transparent uncertainty quantification, sensitivity analysis, and model intercomparison approaches.

6.3 Integration of Human Behavior

Integrating socio-economic dynamics and human decision-making into agri-ecosystem models remains a significant challenge due to the complexity and context-specific nature of human behavior.

Farmers' decisions regarding crop choice, input use, irrigation, and risk management are influenced by a wide range of factors, including economic incentives, institutional constraints, cultural norms, access to information, and individual risk perceptions. Although agent-based models (ABMs) represent a substantial advancement by explicitly modeling heterogeneous actors and their interactions, they require detailed behavioral data and well-defined decision rules that are often difficult to obtain and validate (Berger & Troost, 2014).

Moreover, behavioral assumptions embedded within ABMs may not be transferable across regions or socio-economic contexts, limiting their generalizability (Schlüter et al., 2017). The dynamic feedbacks between human decisions and biophysical processes are also challenging to capture, particularly under rapidly changing climatic and market conditions (Groeneveld et al., 2017). Consequently, inadequate representation of human behavior can introduce additional uncertainty into model outcomes and constrain the usefulness of agri-ecosystem models for policy analysis and long-term planning, highlighting the need for interdisciplinary approaches and improved integration of socio-economic data.

6.4 Policy Translation

Although agri-ecosystem models are widely used to generate projections and scenario analyses, translating model outputs into actionable and effective policy remains a significant challenge. Model results are often complex, probabilistic, and scenario-dependent, making them difficult for policymakers and non-technical stakeholders to interpret and apply in real-world decision-making processes (Pielke, 2007). Uncertainties arising from model structure, parameterization, and input data further complicate the policy translation process, as decision-makers may struggle to assess the robustness and reliability of projected outcomes (Ascough et al., 2008). In addition, mismatches between the spatial and temporal scales of model outputs and policy needs can limit their practical relevance, particularly for short-term planning and local governance (Jones et al., 2017).

Effective policy translation therefore requires clear communication of assumptions, uncertainties, and limitations, as well as the development of decision-support tools, stakeholder engagement frameworks, and co-production approaches that bridge the gap between scientific modeling and policy formulation.

6.5 Future Directions

Agri-ecosystem modeling is poised for significant advancement, driven by rapid improvements in computational capacity, increased availability of high-resolution data, and ongoing methodological innovations. The growing integration of remote sensing, Internet of Things (IoT) sensors, and big data platforms offers new opportunities to enhance model parameterization, calibration, and real-time updating, thereby improving predictive accuracy across multiple spatial and temporal scales (Jones et al., 2017). Advances in machine learning and hybrid modeling approaches that combine process-based models with data-driven techniques are expected to improve the representation of complex, nonlinear interactions within agricultural systems while reducing computational and parameter uncertainties (Reichstein et al., 2019). In addition, increased emphasis on multi-scale and multi-model frameworks can enhance model robustness and facilitate uncertainty quantification through ensemble-based approaches (Wallach et al., 2016).

Future research is also likely to focus on stronger integration of socio-economic processes, participatory modeling, and co-design with stakeholders to improve model relevance for decision-making and policy development (Schlüter et al., 2017). Collectively, these developments have the potential to increase the reliability, transparency, and practical impact of agri-ecosystem models in addressing food security, climate adaptation, and sustainable agricultural management.

7. INTEGRATION WITH REMOTE SENSING AND BIG DATA

The integration of remote sensing, geospatial analytics, and big data technologies is transforming agri-ecosystem modeling by providing high-resolution, real-time, and spatially explicit data for dynamic simulations.

Remote sensing platforms including satellites, drones, and ground-based sensors generate large volumes of data on vegetation health, soil moisture, land-use changes, and environmental conditions. When combined with big data analytics and machine learning techniques, these datasets enable models to capture complex spatiotemporal dynamics, improve predictive accuracy, and provide actionable insights for decision-makers.

Remote sensing provides quantitative information that can be directly incorporated into model parameters, such as crop growth stages, evapotranspiration rates, and biomass production. Geospatial analytics allow these inputs to be mapped across landscapes, supporting spatially explicit modeling that accounts for variability in soil type, topography, climate, and land management practices. Machine learning algorithms can process massive, heterogeneous datasets to identify patterns, detect anomalies, and optimize model calibration, reducing uncertainty in forecasts. Big data streams from sensors, IoT devices, and climate monitoring networks enable near real-time updating of agri-ecosystem models, allowing dynamic simulations to reflect current conditions. This capability supports rapid scenario testing, such as evaluating the impact of sudden weather events, pest outbreaks, or market shocks. By integrating up-to-date information, models can provide stakeholders with timely recommendations, enhancing adaptive management and policy planning.

7.1 Coupling Biophysical and Socio-Economic Systems

Future agri-ecosystem models are expected to place greater emphasis on the explicit coupling of biophysical processes with socio-economic dynamics to better reflect the complex interactions between human decision-making and environmental systems. Farmers' responses to policy interventions, market incentives, technological adoption, and climate variability are shaped by economic conditions, institutional frameworks, risk preferences, and access to information, all of which influence land-use decisions and management practices.

Advanced agent-based models (ABMs) and hybrid modeling frameworks that combine process-based crop and soil models with economic and behavioral components offer a promising pathway for capturing heterogeneous farmer behavior and adaptive responses over time (Berger & Troost, 2014).

In addition, the integration of machine learning techniques with traditional modeling approaches can improve the representation of nonlinear feedbacks and emergent system behavior while reducing reliance on overly simplified assumptions (Reichstein et al., 2019). By more realistically simulating interactions between policy measures, human behavior, and biophysical outcomes, coupled socio-economic–biophysical models can provide richer insights into trade-offs, unintended consequences, and long-term sustainability outcomes, thereby enhancing their value for policy design and strategic decision-making (Schlüter et al., 2017).

7.2 Policy-Driven Modeling Frameworks

Policy driven modeling frameworks are increasingly central to decision making in complex socio environmental systems. These frameworks enable stakeholders—from governments to industry and civil society—to rapidly explore “what if” scenarios, assessing the consequences of alternative policy choices before implementation. They combine data, theory, and simulation tools to help forecast outcomes under different assumptions, quantify trade offs, and identify robust policy options in the face of uncertainty.

A key advantage of policy driven models is their ability to support scenario analysis, allowing users to simulate and compare multiple futures. For example, integrated assessment models can explore how greenhouse gas pricing, renewable energy mandates, or land use regulations might influence emissions trajectories and economic indicators, offering policymakers a structured way to consider long term impacts. Other frameworks, such as agent based models or equilibrium models, can help project how individual actors (e.g., firms, households, or farms) respond to policy changes and how these responses aggregate across systems. These techniques support decisions in areas as diverse as climate adaptation, market regulation, and sustainable intensification of food systems.

7.2.1 Scenario Analysis Tools and Their Roles

Integrated Assessment Models (IAMs)

IAMs combine insights from multiple domains—economy, energy, land use, and climate—to evaluate policy impacts on both environmental and socio economic outcomes. They are widely used to assess climate mitigation and adaptation pathways, quantifying trade offs between economic growth, emissions, and welfare.

Agent Based Models (ABMs)

These bottom up models simulate the behavior and interactions of heterogeneous agents (such as farmers or firms) under different policy scenarios. ABMs are particularly useful in capturing emergent system behavior from individual decisions, which is critical for evaluating policies in complex systems like agriculture or renewable energy transitions.

Dynamic Stochastic General Equilibrium (DSGE) and Computable General Equilibrium (CGE) Models

These macroeconomic tools evaluate policy impacts on market dynamics, prices, and resource allocations under uncertainty. They help stakeholders understand how fiscal, environmental, or trade policies can ripple through economies.

Spatial and Land Use Models

Models like LEAM simulate how alternative land use policies affect urban growth, transportation systems, and environmental outcomes, providing spatially explicit insights into policy trade offs.

Global Systems Models

Large scale models such as International Futures provide integrated projections across sectors (e.g., demographics, health, environment), useful for strategic planning and high level policy evaluation.

7.2.2 Applications in Emerging Challenges

Climate Adaptation and Resilience

Policy experiments supported by advanced modeling help stakeholders test adaptation strategies—such as infrastructure investments, insurance schemes, or community based measures—under a range of climate scenarios. They enable planners to assess not only physical impacts but also socio economic outcomes (e.g., costs, equity) and interactions with other risks.

Market Volatility and Economic Policy

Economic models with stochastic components allow analysts to evaluate how regulatory decisions, commodity price shocks, or monetary interventions influence market stability. By incorporating uncertainty, such frameworks help policymakers identify strategies that maintain resilience under stress.

Sustainable Intensification

In agriculture and land management, models that integrate environmental, economic, and social dimensions can inform policies aimed at increasing productivity while minimizing ecological footprints. For example, agent based and equilibrium models support assessments of subsidies, production standards, or land use incentives on both yields and resource use efficiency.

7.2.3 Benefits, Challenges and Considerations

Policy driven modeling frameworks facilitate evidence based decision making by making implicit assumptions explicit and enabling systematic comparison of alternative strategies. They help illuminate potential unintended consequences, enhance transparency, and build consensus among stakeholders. However, these frameworks also require careful calibration, quality data, and clear communication of uncertainty to avoid misleading conclusions. Integrating diverse models and engaging stakeholders throughout the modeling process are essential best practices to ensure relevance and credibility. While integration of remote sensing and big data enhances the accuracy, responsiveness, and scalability of models, challenges remain.

These include managing heterogeneous and large-volume datasets, ensuring data quality and completeness, and addressing computational demands for real-time analytics. Furthermore, careful interpretation of outputs and transparent communication of uncertainties are essential to support effective policy and practice.

By combining dynamic modeling with remote sensing and big data, agri-ecosystem simulations can provide robust, evidence-based guidance for sustainable agriculture, climate adaptation, and resource management, transforming the way policy decisions are made and implemented.

CONCLUSION

Dynamic agri-ecosystem modeling has emerged as a cornerstone of modern agricultural research and policy analysis, providing essential tools to understand and manage the complexity of agricultural systems. By explicitly representing interactions among biophysical processes, management practices, socio-economic drivers, and policy interventions, these models enable a systems-level perspective that is critical for addressing contemporary challenges such as climate change, food insecurity, environmental degradation, and sustainable intensification. Their capacity to simulate dynamic behavior over extended time horizons allows stakeholders to explore alternative futures and assess the long-term consequences of decisions made today.

This chapter has highlighted the diversity of agri-ecosystem modeling approaches, including process-based crop models, land-use and spatial simulations, biogeochemical models, agent-based frameworks, and system dynamics models. Each approach offers distinct strengths, ranging from detailed representations of crop physiology and soil processes to higher-level analyses of socio-economic feedbacks and policy outcomes. Collectively, these approaches provide complementary insights across spatial and temporal scales, supporting integrated assessments of productivity, environmental sustainability, and socio-economic resilience. Dynamic simulations play a vital role in evidence-based policy and practice by enabling scenario analysis, risk evaluation, and systematic comparison of alternative management and policy options.

They assist decision-makers in identifying trade-offs, anticipating unintended consequences, and designing interventions that balance agricultural productivity with environmental protection and social objectives. However, challenges related to data availability, model uncertainty, representation of human behavior, and effective communication of results continue to constrain broader adoption and policy impact.

Future progress in agri-ecosystem modeling will depend on advances in data integration, computational capacity, and interdisciplinary collaboration. The growing incorporation of remote sensing, big data analytics, machine learning, and hybrid socio-biophysical frameworks offers significant potential to enhance model accuracy, scalability, and relevance. As agricultural systems face increasing pressure from climatic variability, demographic change, and resource constraints, agri-ecosystem models will remain indispensable for guiding sustainable agricultural policies.

REFERENCES

Ascough, J. C., et al. (2008). Future research challenges for watershed-scale modeling. Transactions of the ASABE, 51(5), 1713–1725.

Berger, T., & Troost, C. (2014). Agent-based modelling of climate adaptation and mitigation options in agriculture. Journal of Agricultural Economics, 65(2), 323–348.

Confalonieri, R., et al. (2016). Uncertainty in crop model predictions: What is it, how to estimate it, and how to reduce it. European Journal of Agronomy, 70, 1–13.

DAESim. (2025). A dynamic agro-ecosystem simulation model for natural capital assessment. Ecological Modelling.

DayCent. (2025). DayCent: Daily time-step CENTURY model.

Groeneveld, J., et al. (2017). Theoretical foundations of human decision-making in agent-based land use models: A review. Environmental Modelling & Software, 87, 39–48.

Jones, J. W., Antle, J. M., Basso, B., Boote, K. J., Conant, R. T., Foster, I., & Godfray, H. C. J. (2017). Toward a new generation of agricultural system data, models, and knowledge products. Agricultural Systems, 155, 269–288.

Jun, Y. (2023). Simulating sustainable agricultural ecosystems: An introduction to agro-ecosystem modeling. Geoinformatics & Geostatistics: An Overview.

Lalani, B., Parsons, D., Ahmed, M., et al. (2025). Simulations using APSIM suggest that conservation agriculture sustains protein yield under changing climate dynamics in northern Mozambique. BMC Plant Biology, 25, Article 1556.

Liu, J., Hertel, T. W., Taheripour, F., Zhu, T., & Ringler, C. (2019). International trade buffers the impact of future irrigation shortfalls. Environmental Modelling & Software, 122, 104527.

Nature Research Intelligence. (2025). Agricultural production systems simulation for sustainable agriculture.

Pielke, R. A. (2007). The honest broker: Making sense of science in policy and politics. Cambridge University Press.

Reichstein, M., et al. (2019). Deep learning and process understanding for data-driven Earth system science. Nature, 566, 195–204.

Rosenzweig, C., et al. (2014). Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proceedings of the National Academy of Sciences, 111, 3268–3273.

Schluter, M., et al. (2017). A framework for mapping and comparing behavioural theories in models of social–ecological systems. Ecological Economics, 131, 21–35.

ScienceDirect. (2012). System dynamics model for analyzing eco-agriculture system with policy recommendations. Ecological Modelling.

Socio-technical agent-based simulation model for smart agriculture adoption. (2025). Nature.

Van Ittersum, M. K., Cassman, K. G., Grassini, P., Wolf, J., Tittonell, P., & Hochman, Z. (2013). Yield gap analysis with local to global relevance. Field Crops Research, 143, 4–17.

Verburg, P. H., & Overmars, K. P. (2007). Dynamic simulation of land-use change trajectories with the CLUE-S model. Springer.

Wallach, D., Makowski, D., Jones, J. W., & Brun, F. (2016). Working with dynamic crop models: Methods, tools and examples for agriculture and environment. Academic Press.

CHAPTER 3
CLIMATE-SMART AND SUSTAINABLE ANIMAL FEEDING STRATEGIES: UTILIZATION OF AGRO-INDUSTRIAL BY-PRODUCTS, CROP RESIDUES, AND TROPICAL ESSENTIAL OILS

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INTRODUCTION

In sub-Saharan Africa, with Nigeria as a prominent example, animal agriculture remains a cornerstone of rural livelihoods, employment generation, income diversification, and national food and nutrition security. Livestock production contributes substantially to household resilience by providing meat, milk, eggs, manure, traction, and financial buffers against crop failure. Despite its socio-economic importance, the sector continues to face persistent and interrelated challenges, including escalating feed costs, antimicrobial resistance, land-use pressure from competing agricultural and non-agricultural demands, climate variability, and generally low productivity across both ruminant and monogastric production systems (Anaso & Anaso, 2025; Anaso & Olafadehan, 2025). These constraints have limited the capacity of livestock systems to meet the rapidly growing demand for animal-source foods driven by population growth and urbanization.

A major structural bottleneck is the heavy reliance on conventional feed ingredients such as maize, soybean meal, and groundnut cake. These feedstuffs are increasingly unsustainable due to direct competition with human food systems, dependence on imports, exposure to global market shocks, and pronounced price volatility (FAO, 2022; Makkar, 2018; Olafadehan et al., 2023a,b). As a consequence, feed alone accounts for approximately 60–70% of total livestock production costs, rendering animal production economically precarious for smallholder and medium-scale farmers. This economic pressure is particularly acute in Nigeria and other West African countries, where access to credit and risk-mitigation mechanisms is limited.

Climate change has further compounded these challenges by disrupting feed availability and quality. Reduced pasture regeneration, increased frequency and intensity of droughts, prolonged dry seasons, and rising ambient temperatures have intensified heat stress and seasonal feed shortages, thereby depressing animal performance and reproductive efficiency. In parallel, global and regional restrictions on the use of antibiotic growth promoters—driven by concerns over antimicrobial resistance and food safety—have heightened the urgency to identify safe, natural, and effective alternatives that can sustain animal health and productivity without posing risks to public health (Windisch et al., 2008; Patra & Saxena, 2011; Anaso & Alagbe, 2025b,c).

Against this backdrop, agro-industrial by-products, crop residues, and tropical essential oils have emerged as viable and climate-smart feeding strategies for tropical livestock systems. These resources are locally abundant yet underutilized, and their strategic use aligns strongly with circular bioeconomy principles by converting agricultural waste streams into value-added animal protein. When appropriately processed and judiciously incorporated into livestock diets, they have demonstrated significant potential to improve nutrient utilization, enhance animal performance, increase system resilience to climatic shocks, and reduce the environmental footprint of animal agriculture (Anaso, 2025a–e; Anaso & Anaso, 2025; Olafadehan et al., 2023b; Makkar & Ankers, 2014). Their adoption also offers a pathway to reducing feed costs and improving the profitability and sustainability of smallholder-dominated production systems.

The scope for sustainable animal feeding has been further expanded by recent advances in phytogenic feed additives, particularly essential oils derived from tropical plant species such as Piliostigma thonningii, Daniellia oliveri, and Zingiber officinale. These essential oils are rich in bioactive compounds with antimicrobial, antioxidant, anti-inflammatory, and rumen-modulating properties, enabling them to favorably influence gut microbial ecology, nutrient metabolism, and host immune responses. Consequently, they are increasingly recognized as promising natural alternatives to synthetic growth promoters and chemotherapeutics in tropical livestock systems (Greathead, 2003; Anaso, 2023a; Anaso et al., 2025a–g). Collectively, these innovations provide a robust scientific and practical foundation for reorienting animal agriculture in Nigeria and West Africa toward more resilient, cost-effective, and environmentally sustainable production pathways.

1. AGRO-INDUSTRIAL BY-PRODUCTS AND CROP RESIDUES AS ALTERNATIVE FEED RESOURCES

In Nigeria and across West Africa, agricultural residues and agro-industrial by-products (AIBPs) constitute a vast but largely underexploited feed resource base with considerable potential to transform livestock production systems.

Commonly available materials include sugarcane scrapings, cassava peels, maize bran, rice bran, wheat offal, oilseed cakes, brewers' dried grains, and residues generated from cereal and legume harvesting. These by-products are produced in large quantities as a consequence of expanding crop production and agro-processing activities, yet a substantial proportion remains underutilized or improperly disposed of, contributing to environmental pollution rather than productive use (Anaso, 2025b). Although AIBPs and crop residues are often characterized by high fiber content, low crude protein levels, imbalanced mineral profiles, and the presence of anti-nutritional factors, their abundance, local availability, and relatively low cost make them attractive alternatives to conventional feed ingredients when appropriate processing and supplementation strategies are employed (Devendra, 2011; Makkar, 2018; Anaso et al., 2024b). In regions where feed costs account for the largest share of livestock production expenses, the strategic use of these resources offers a practical pathway to reducing dependence on imported or human-competitive feedstuffs such as maize and soybean meal.

Among the various upgrading approaches, biological processing techniques—particularly solid-state fermentation using lignocellulolytic fungi such as Pleurotus ostreatus—have proven highly effective in improving the nutritive value of fibrous residues. Fermentation enhances crude protein content through microbial biomass synthesis, reduces lignin, cellulose, and neutral detergent fiber fractions, and improves digestibility and palatability by partially degrading complex cell wall structures (Anaso, 2025a,b; Anaso & Olafadehan, 2025; Olafadehan et al., 2023a). These biochemical modifications translate into improved rumen and hindgut fermentation efficiency and greater nutrient availability to the host animal. Empirical studies in sheep and goats have demonstrated that diets incorporating biodegraded sugarcane scrapings significantly improve feed intake, apparent nutrient digestibility, and feed efficiency. Beyond nutritional benefits, improvements in hematological and biochemical indices, thermoregulatory stability, and reproductive performance have been observed, indicating broader physiological advantages and enhanced resilience under tropical environmental conditions (Anaso et al., 2024b; Anaso & Alagbe, 2025a).

Such findings underscore the dual nutritional and health-promoting value of biologically processed AIBPs in small ruminant production systems. In addition to agro-industrial by-products, indigenous browse species and crop residues such as Parkia biglobosa foliage represent important, climate-adapted feed resources. Partial replacement of concentrate diets with P. biglobosa leaves in goats has been shown to improve rumen fermentation patterns, nitrogen utilization, microbial protein synthesis, and growth performance, reflecting more efficient use of dietary nitrogen and enhanced rumen microbial activity (Olafadehan et al., 2023b). These outcomes highlight the strategic role of locally available browse plants in reducing feed costs while maintaining or improving animal productivity.

Collectively, these findings emphasize the importance of locally tailored feeding strategies that integrate agro-industrial by-products, crop residues, and indigenous browse resources. Such approaches not only reduce reliance on imported concentrates but also promote resource-use efficiency, environmental sustainability, and economic viability of livestock production systems in Nigeria and the wider West African region.

2. TROPICAL ESSENTIAL OILS AS PHYTOGENIC FEED ADDITIVES

2.1 Chemical Composition and Bioactive Properties

Essential oils are complex and highly dynamic mixtures of volatile secondary plant metabolites, predominantly composed of terpenoids (monoterpenes and sesquiterpenes), phenylpropanoids, and other aromatic compounds. These metabolites are biosynthesized as part of plant defense systems and ecological signaling mechanisms, and their chemical diversity underpins a broad spectrum of biological activities. Tropical essential oils are particularly notable for their richness in bioactive constituents, which confer multifunctional effects on gastrointestinal microbial populations, host metabolic pathways, immune regulation, and oxidative balance in livestock (Anaso, 2023a). Advanced phytochemical characterization using gas chromatography–mass spectrometry has revealed that Piliostigma thonningii essential oil is dominated by monoterpenes and sesquiterpenes.

These include β-pinene, limonene, α-muurolene, terpinen-4-ol, and related terpenoid fractions (Anaso, 2023b).These compounds possess well-documented antimicrobial, antioxidant, and anti-inflammatory properties. Mechanistically, they exert antimicrobial action through disruption of microbial cell membranes, increased membrane permeability, leakage of intracellular constituents, and inhibition of key metabolic enzymes. Such actions selectively suppress pathogenic and inefficient microbial populations while allowing beneficial fermentative microbes to proliferate, thereby improving gut microbial balance.

In addition to their antimicrobial effects, many of these terpenoid compounds function as potent free-radical scavengers, mitigating oxidative stress by neutralizing reactive oxygen species and stabilizing cellular membranes. Their capacity to modulate enzyme activity further influences digestive processes and metabolic efficiency, contributing to improved nutrient utilization and physiological resilience in animals exposed to nutritional and environmental stressors.

Comparable bioactive profiles have been reported for essential oils derived from other tropical plant species, including Daniellia oliveri and Zingiber officinale. These oils are rich in structurally diverse terpenoids and phenolic compounds that exhibit synergistic antimicrobial, antioxidant, and immunomodulatory effects (Patra & Yu, 2012; Benchaar et al., 2008). Experimental studies have demonstrated that such oils can modulate rumen and hindgut fermentation patterns, suppress enteric pathogens, enhance immune competence, and improve overall animal performance (Anaso, 2025c,d).

Collectively, the complex chemical composition and multifunctional bioactivity of tropical essential oils position them as highly promising phytogenic feed additives for tropical livestock systems. Their ability to simultaneously influence microbial ecology, metabolic efficiency, and host defense mechanisms provides a strong scientific basis for their inclusion in sustainable, antibiotic-free feeding strategies tailored to the challenges of animal production in Nigeria and the wider West African region.

3.EFFECTS OF ESSENTIAL OILS ON DIGESTIBILITY, RUMEN AND CAECAL FERMENTATION

An expanding body of controlled feeding trials and mechanistic studies provides strong evidence that essential oil supplementation markedly enhances nutrient digestibility and fermentation efficiency across a wide range of livestock species. In monogastric systems, particularly rabbits, dietary inclusion of Piliostigma thonningii essential oil has consistently resulted in significant improvements in the apparent digestibility of dry matter, crude protein, and structural carbohydrates. These responses indicate more efficient enzymatic degradation of dietary components and improved absorptive capacity of the gastrointestinal tract (Anaso et al., 2024a,d). Enhanced fiber digestibility is of particular importance in rabbit production, where efficient caecal fermentation is critical for energy supply and microbial protein synthesis.

In parallel with improved digestibility, P. thonningii essential oil supplementation has been shown to stimulate total volatile fatty acid production while significantly reducing ammonia nitrogen concentrations in the caecum (Anaso et al., 2025b; Anaso et al., 2025c). Elevated volatile fatty acid concentrations reflect increased microbial fermentative activity and improved conversion of dietary substrates into metabolizable energy, whereas lower ammonia nitrogen levels indicate more efficient capture of nitrogen into microbial biomass rather than excessive deamination and nitrogen loss. Collectively, these changes are indicative of enhanced microbial efficiency, improved nitrogen utilization, and a more stable and productive caecal ecosystem.

In ruminant animals, essential oils exert pronounced modulatory effects on rumen microbial ecology and fermentation pathways. Experimental evidence demonstrates that essential oil supplementation selectively suppresses methanogenic archaea and protozoal populations while favoring the proliferation of propionate-producing bacterial species. This targeted microbial modulation alters fermentation end-product profiles in a manner that is energetically advantageous to the host animal.

Supplementation with P. thonningii essential oil has been associated with increased concentrations of propionate and butyrate, reduced acetate-to-propionate ratios, and lower methane-related fermentation indices, collectively enhancing the efficiency of ruminal energy metabolism (Anaso & Alagbe, 2025c; Calsamiglia et al., 2007).

From a physiological and environmental perspective, these fermentation shifts are highly significant. Propionate serves as the primary glucogenic precursor in ruminants, directly supporting glucose synthesis and productive functions such as growth, lactation, and reproduction. Concurrent reductions in methane formation represent a redirection of metabolic hydrogen toward productive pathways rather than gaseous energy losses, thereby increasing the proportion of dietary energy retained by the animal. Moreover, suppression of excessive ruminal ammonia production improves nitrogen retention and reduces nitrogen excretion into the environment.

Overall, the evidence indicates that tropical essential oils, particularly those derived from P. thonningii, act as effective rumen and hindgut modifiers that enhance digestive efficiency, optimize fermentation dynamics, and improve nutrient utilization. These effects underpin the observed improvements in animal performance and contribute to reduced environmental footprints, reinforcing the value of essential oils as functional, climate-smart feed additives in tropical livestock production systems.

4. GROWTH PERFORMANCE, FEED EFFICIENCY, AND CARCASS TRAITS

A growing body of empirical evidence demonstrates that supplementation with tropical essential oils produces consistent and biologically meaningful improvements in growth performance and feed utilization across both monogastric and ruminant livestock species. In rabbits, dietary inclusion of essential oils derived from Piliostigma thonningii and Daniellia oliveri has been shown to significantly increase final body weight and average daily gain while simultaneously improving feed conversion ratio, indicating more efficient transformation of feed nutrients into body tissue.

These performance gains are typically achieved without depressing voluntary feed intake, suggesting that essential oils enhance digestive efficiency and metabolic utilization rather than simply stimulating appetite. Importantly, sensory evaluation and physicochemical analyses have revealed no adverse effects on meat colour, flavour, tenderness, or overall organoleptic acceptability, confirming that productivity gains do not compromise consumer-relevant quality attributes (Anaso et al., 2024c; Anaso et al., 2025b).

The mechanisms underpinning these improvements are multifactorial and include enhanced nutrient digestibility, stabilization of gut microbial populations, improved nitrogen retention, and reduced metabolic energy losses associated with subclinical inflammation and oxidative stress. By modulating intestinal and caecal fermentation patterns, essential oils promote a more favorable microbial ecosystem that supports efficient enzymatic activity and nutrient absorption, thereby translating into superior growth efficiency.

In ruminant systems, particularly sheep and cattle, essential oil supplementation has been associated with notable improvements in carcass characteristics and meat quality parameters. Enhanced dressing percentage and carcass yield reflect improved muscle accretion and reduced non-carcass tissue deposition, while favorable shifts in primal cut distribution indicate more efficient partitioning of nutrients toward economically valuable carcass components. Improvements in water-holding capacity further contribute to reduced drip and cooking losses, enhancing meat juiciness, processing yield, and shelf-life stability (Anaso et al., 2025f; Anaso et al., 2025h).

Of particular nutritional and commercial significance are the alterations in meat lipid profiles associated with essential oil inclusion. Consistent reductions in saturated fatty acid concentrations, coupled with increases in polyunsaturated fatty acids and conjugated linoleic acid, have been reported in meat from essential oil–supplemented animals. These changes are indicative of modified rumen biohydrogenation pathways and improved lipid metabolism and are widely recognized for their positive implications for human health, including cardiovascular risk reduction. Consequently, essential oil supplementation not only enhances production efficiency but also elevates the functional and market value of animal-derived foods (Anaso & Alagbe, 2025b).

Taken together, these findings underscore the dual role of tropical essential oils as performance-enhancing and quality-modifying feed additives. Their capacity to improve growth rates, feed efficiency, carcass yield, and meat nutritional profile positions them as strategic tools for sustainable livestock intensification in tropical production systems, where economic efficiency, product quality, and consumer health considerations must be simultaneously addressed.

5. PHYSIOLOGICAL HEALTH, IMMUNE FUNCTION, AND OXIDATIVE STRESS MODULATION

Essential oils exert multifaceted and biologically meaningful effects on animal health and physiological resilience that extend well beyond conventional growth and performance indices. Their influence on systemic immunity is particularly noteworthy. Dietary supplementation with tropical essential oils has been consistently associated with significant increases in serum total protein, albumin, and globulin concentrations, reflecting improved protein metabolism, enhanced hepatic synthetic activity, and strengthened humoral immune function. Concurrent elevations in immunoglobulin classes IgG, IgA, and IgM further indicate heightened immune surveillance, improved mucosal immunity, and greater capacity to mount effective responses against pathogenic challenges. These immunomodulatory effects are especially valuable in tropical production systems, where animals are routinely exposed to high pathogen loads and environmental stressors (Anaso et al., 2025a; Anaso et al., 2025d).

In parallel, essential oils play a critical role in modulating oxidative status and endocrine stress responses. Their rich content of phenolic compounds, terpenoids, and other bioactive constituents enhances endogenous antioxidant defense systems by upregulating key enzymes such as superoxide dismutase, catalase, and glutathione peroxidase. This enzymatic activation promotes efficient scavenging of reactive oxygen species and limits cellular and tissue damage. Correspondingly, marked reductions in lipid peroxidation biomarkers, particularly malondialdehyde, have been reported, indicating improved membrane integrity and reduced oxidative injury.

Essential oil supplementation has also been associated with lower circulating cortisol concentrations, suggesting attenuation of hypothalamic pituitary adrenal axis activation and improved stress resilience under both nutritional and environmental challenges (Anaso et al., 2025a; Patra, 2011).

These antioxidant and anti-stress effects translate into tangible physiological adaptations, particularly under conditions of thermal stress that are common in tropical and subtropical regions. Thermoregulatory responses, including reductions in rectal temperature and respiration rate, have been consistently observed in rabbits, sheep, and goats receiving essential oil–supplemented diets. Such responses reflect improved heat dissipation efficiency, reduced metabolic heat load, and enhanced homeostatic regulation. By stabilizing internal body temperature and minimizing respiratory distress, essential oils help preserve feed intake, metabolic efficiency, and immune competence during periods of elevated ambient temperature (Anaso et al., 2025d; Anaso & Alagbe, 2025a; Anaso et al., 2025d).

Collectively, these findings position tropical essential oils as functional feed additives with pronounced health-promoting, adaptogenic, and resilience-enhancing properties. Their ability to strengthen immune defenses, mitigate oxidative and endocrine stress, and improve thermoregulatory capacity underscores their strategic relevance for sustainable livestock production in hot-climate environments, where maintaining animal health and welfare is as critical as maximizing productivity.

Reproductive Performance and Fertility Outcomes

There is growing evidence that essential oils have a positive impact on fertility and reproductive performance. Rabbits and rams fed with tropical essential oils showed improvements in semen volume, sperm concentration, motility, viability, testosterone levels, and decreases in aberrant sperm cells (Anaso et al., 2024a; Anaso et al., 2024d; Anaso et al., 2025d). These advantages are strongly associated with better metabolic health and increased antioxidant defense of reproductive organs (Anaso, 2024).

Environmental and Climate-Smart Implications

The integration of agro-industrial by-products, crop residues, and essential oils into livestock feeding systems contributes significantly to climate-smart agriculture by:

- Reducing reliance on synthetic antibiotics and chemotherapeutics
- Lowering enteric methane emissions through rumen modulation
- Recycling agricultural waste and reducing environmental pollution
- Improving feed efficiency, nitrogen retention, and resource-use efficiency

These strategies align strongly with circular bioeconomy concepts and sustainable livestock intensification pathways advocated for West Africa (Makkar, 2018; Anaso & Anaso, 2025).

6. CHALLENGES AND FUTURE PERSPECTIVES

Despite the growing body of experimental and field-based evidence supporting the efficacy of agro-industrial by-products, crop residues, and tropical essential oils in livestock feeding, their widespread adoption in Nigeria and across West Africa remains constrained by several structural, technical, and institutional challenges. A major limitation is the inherent variability in the phytochemical composition of essential oils, which is influenced by plant genotype, agro-ecological conditions, stage of harvest, and extraction methods. This inconsistency complicates product standardization, compromises repeatability of animal responses, and undermines farmer confidence. Closely related to this challenge is the absence of harmonized quality assurance protocols and dosage guidelines, resulting in uncertainty regarding optimal inclusion levels, potential toxicity thresholds, and long-term safety under diverse production systems.

Inadequate processing and value-addition infrastructure further restrict scalability, particularly for smallholder farmers who dominate livestock production in the region. Limited access to cost-effective technologies for drying, fermentation, oil extraction, and storage increases production costs and reduces the economic competitiveness of these alternative feed resources relative to conventional feeds.

High initial capital requirements, weak supply chains, and fluctuating availability of raw materials also contribute to slow uptake. Moreover, regulatory frameworks governing phytogenic feed additives and non-conventional feed ingredients remain underdeveloped or poorly enforced in many West African countries, creating ambiguity in product registration, quality control, and commercialization pathways (Anaso & Salihu, 2025; Alhassan & Anaso, 2024).

To facilitate large-scale adoption, there is a critical need for coordinated, multi-location and multi-species studies that capture agro-ecological variability and production realities across the region. Long-term feeding trials and toxicological assessments are essential to establish safety margins, cumulative effects, and potential interactions with other dietary components. Equally important are robust socioeconomic and cost–benefit analyses that quantify economic returns, labor requirements, and risk profiles from the perspective of smallholder and commercial producers, thereby strengthening the evidence base for policy and investment decisions.

Looking forward, future research should prioritize the development of integrated feeding systems that strategically combine crop residues, agro-industrial by-products, and phytogenic additives into cohesive, climate-smart ration models. Such systems-based approaches, supported by adaptive formulation tools and locally relevant feeding guidelines, can bridge the gap between experimental findings and on-farm implementation. Translating research into practice will also require strengthened policy support, effective extension and advisory services, and well-structured public–private partnerships to promote technology transfer, build farmer capacity, and stimulate private sector investment. Collectively, these measures will be pivotal in unlocking the full potential of alternative feed resources and phytogenics for sustainable livestock development in Nigeria and West Africa.

CONCLUSION

Agro-industrial by-products, crop residues, and tropical essential oils constitute highly practical and climate-smart feeding strategies with substantial potential to transform livestock production systems in Nigeria and across West Africa.

Empirical evidence from controlled feeding trials and on-farm studies consistently demonstrates that these resources can enhance animal productivity through improved feed intake, nutrient digestibility, growth performance, and reproductive efficiency, while simultaneously promoting animal health via improved immune competence, antioxidant status, and metabolic stability. Their utilization also contributes to superior product quality, including improved carcass characteristics, healthier fatty acid profiles in meat and milk, and reduced reliance on synthetic growth promoters and antibiotics.

Beyond productivity gains, the integration of these alternative feed resources directly addresses major environmental and socio-economic challenges facing African animal agriculture. The valorization of agro-industrial by-products and crop residues reduces feed–food competition, lowers dependence on imported conventional feed ingredients, and supports circular bioeconomy principles by converting agricultural waste streams into valuable livestock inputs. Similarly, the inclusion of tropical essential oils as phytogenic feed additives offers a natural approach to improving feed efficiency and mitigating enteric methane emissions, thereby reducing the environmental footprint of ruminant production and enhancing resilience to climate change.

Strategic and context-specific integration of these resources provides a clear pathway toward lowering production costs, improving adaptive capacity to climatic stressors, and strengthening food and nutrition security for rapidly growing human populations in the region. However, realizing their full potential will require coordinated efforts in targeted research, including dose optimization, long-term safety assessment, and system-level evaluations; supportive regulatory frameworks to ensure quality control and farmer confidence; and robust capacity-building initiatives to facilitate adoption by smallholder and commercial producers alike. With sustained investment and policy support, these climate-smart feeding innovations have the capacity to significantly advance sustainable, resilient, and economically viable animal agriculture across Africa.

REFERENCES

Al-hassan, S.M., Anaso, E.U. (2024). Physicochemical properties, isolation, and identification of Pseudomonas aeruginosa from the skin of some selected pond-grown catfish from Gwagwalada Area Council, Abuja. Eastern Journal of Agricultural and Biological Sciences, 4(2), 1-12. DOI: 10.53906/ejabs.v4i2.309.

Anaso E.U. (2025a). Body thermoregulatory adaptations and reproductive potentials of yankassa rams fed diets containing urea-molasses treated cassava peel ensiled with caged-layer droppings. TURJAF 2025 Congress / TURJAF 2025 Kongresine tam metin yüklemek için. IV. International Congress of the Turkish Journal of Agriculture - Food Science and Technology (TURJAF 2025), hosted by Niğde Ömer Halisdemir University and organized by Turkish Science and Technology Publishing (TURSTEP), held on April 28–30, 2025, in Niğde, Türkiye.

Anaso E.U. (2025e). Nutritive value, feed intake and blood profile of Yankassa Rams Supplemented Camel's Foot (Piliostigma Thonningii) Essential Oil-Based Diet. TURJFAS 7(2): 231-241 (2025) DOI: https://doi.org/10.53663/turjfas. 1718783

Anaso EU, Olafadehan OA, Chibuogwu JC, Addass PA, Zubairu H, Joel JO. (2025d). Physiological Responses and Reproductive Potential of Yankassa Rams Supplemented Milne-Rech Seed Essential Oil-Based Diet. Discovery Agriculture 2025; 11: e10da3127

Anaso EU. (2025c). Immune Status, Reproductive Potential, Caecal Microbial and Fermentative Characteristics of Rabbits Supplemented Rolfe (Daniellia Oliveri) Leaf Extract Essential Oil Based Diet. Discovery 2025; 61: e19d3121 doi:https://doi.org/10.54905/disssi.v61i338.e19d3121

Anaso EU. Babalola M, Fidelis ES, Agada IC, Adediran MA. (2025e). Evaluation of feed intake and hematological profile of West Africa dwarf does fed with Piliostigma thonningii seed essential oil-based diet. Science Letters 2025; 13(2):1325300sl. DOI: https://doi.org/10.47262/SL/13.2.132025300

Anaso EU., Alagbe.J.O. (2025a). Body thermoregulatory adaptation and blood serum mineral metabolic profile of rabbits supplemented camel's foot (schum) seed essential oil based diet. Journal of Chemistry Science. 2025, 2(1): 1-6. DOI: https://doi.org/10.61784/jcs3002.

Anaso EU., Olurotimi A. olafadehan and ijeoma C. Chibuogwu (2025c). A systematic review on phytogenic feed supplements on the nutritive effects, physiological responses and reproductive parameters in Rabbits. J. Agr. Fac. Düzce. Uni., v. 3, i. 1, pp. 67-79, 2025.

Anaso, E. U. (2025b). Solid-state fermentation of crop residues and agro-industrial byproducts: A sustainable approach to small ruminant production for economic development, resource efficiency, and SDG achievement in Africa. In E. E. Osuji (Ed.), Social Dimensions of Economic Development: Sustainability and Global Goals – 2025 (pp. 49–75). İstanbul, Türkiye: Haliç Publishing House. ISBN: 979-8-89695-168-1. Copyright © Haliç Yayınevi. Published: 19 September 2025. Available at: https://www.halicyayinevi.com/social

Anaso, E. U.; Anaso, J. N. (2025). Solid-State Fermentation of Crop Residues and Agro-Industrial Byproducts in Small Ruminant Production: A Review. Insights Anim Sci 2025. https://doi.org/10.69917/ias.02.02-04.

Anaso, E., Fidelis, E. S., & Salihu, A.-H. M. (2025f). Carcass and Meat Quality of Yankassa Rams Fed Piliostigma Thonningii Essential Oil-Supplemented Diet. Turkish Journal of Agriculture - Food Science and Technology, 13(11), 3276–3284. https://doi.org/10.24925/turjaf.v13i11.3276-3284.7945

Anaso, E.U. (2023a). Bioactive compounds of Piliostigma thonningii essential oil detected by gas chromatography-mass spectrometry. Eastern Journal of Agricultural and Biological Sciences, 3(2), 68-72. Retrieved from link.

Anaso, E.U. (2023b). Phytogenics and essential oil supplementation in rabbit and monogastrate production: A panacea to improved animal production and antibiotic resistance challenges in Nigeria. Eastern Journal of Agricultural and Biological Sciences, 3(2), 45-51. ISSN: 2753-3247.

Anaso, E.U. (2024). Macro and Micro Anatomy of the Male Genitalia of the Nigerian Laughing Dove (Spilopelia senegalensis). Eastern Journal of Agricultural and Biological Sciences, 4(3), 31–44. https://doi.org/10.53906/ejabs.v4i3.341

Anaso, E.U. (2025d). Body Thermoregulatory Adaptation and Blood Metabolic Profile of Rabbits Supplemented Rolfe (Daniellia oliveri) Leaf Extract Based Diet. Journal Science Letters (132025220-SL). DOI: https://doi.org/10.47262/SL/13.2.132025220

Anaso, E.U. and Alagbe, J.O. (2025b). Eco-Friendly Feeding Strategies: Effects of Ginger (Zingiber Officinale) Essential Oil on Carcass Yield and Meat Quality in White Fulani (Bunaji) Bulls. Research in: Agricultural & Veterinary Sciences Vol.9, No.3, 2025, pp.106-120 https://doi.org/10.62476/ravs.93106

Anaso, E.U. and Alagbe, J.O. (2025c). Nutrient digestibility, rumen fermentation and nitrogen utilization of Yankassa Rams supplemented Milne-Rech (Piliostigma thonningii Schum) essential oil-based diet. Research in: Agricultural & Veterinary Sciences Vol.9, No.3, 2025, pp.169-180 https://doi.org/10.62476/ravs.93169

Anaso, E.U. and Alagbe, J.O., Abdulbasit A. Aderibigbe, Joy N. Anaso and Emeka S. Fidelis. (2025g). Dietary inclusion of ginger (zingiber officinale) essential oil as a sustainable feeding strategy: effects on carcass characteristics, meat fatty acid composition, and quality attributes in Holstein Friesian × white Fulani bulls. Int. J. Agric. Environ. Food Sci. 2025; 9 (4): 1361-1373. DOI: https://doi.org/10.31015/2025.4.36

Anaso, E.U., Olafadehan, O.A. (2025). Nutritive value, feed intake and blood profile of buckling goats fed diets containing Pleurotus ostreatus biodegraded sugarcane scrapings. Archiva Zootechnica, 28:1, 61-76, 2025 DOI: 10.2478/azibna-2025-0004.

Anaso, E.U., Olafadehan, O.A., Chibuogwu, I.C. (2023). Semen characteristics of rabbits fed Camel's Foot (Piliostigma thonningii) essential oil supplemented diet. Discovery, 59, e36d1037.

Anaso, E.U., Olafadehan, O.A., Chibuogwu, I.C. (2025a). Nutritive effects and physiologic responses of rabbits supplemented with Camel's Foot (Piliostigma thonningii) essential oil-based diet. Veterinarski Archiv, 2025. DOI: 10.24099/vet.arhiv.2669

Anaso, E.U., Olafadehan, O.A., Chibuogwu, I.C., Alagbe, J.O. (2024a). Seminal morphology and organ morphometrics of rabbit bucks fed

Piliostigma thonningii essential oil supplemented diet. Science Letters, 12(2), 70-75. DOI: 10.47262/SL/12.2.132024280

Anaso, E.U., Olafadehan, O.A., Chibuogwu, I.C., Shoyombo, A.J. (2025b). Nutrient digestibility, growth performance, cecal microbial profile, and fermentation characteristics of rabbit bucks fed Piliostigma thonningii essential oil supplemented diet. Biotechnology in Animal Husbandry, 41(1), 37-55, 2025 https://doi.org/10.2298/BAH2302205K

Anaso, E.U., Olafadehan, O.A., Emeka, F.S. (2024c). Carcass and meat quality of rabbits supplemented with Camel's Foot (Piliostigma thonningii) essential oil-based diet. Archiva Zootechnica 27:2, 36-51, 2024 DOI: 10.2478/azibna-2024-0013

Anaso, E.U., Olafadehan, O.A., Shoyombo, A.J., Emeka, F.S. (2024b). Body weight, scrotal parameters, and semen characteristics of Kano Brown bucks fed Pleurotus ostreatus solid-state fermented sugarcane scrapings. Turkish Journal of Food and Agricultural Science, DOI: https://doi.org/10.53663/turjfas.1486383.

Anaso, E.U., Olurotimi A. Olafadehan, Ijeoma C. Chibuogwu, Ayoola J. Shoyombo, Samuel Mailafia, Joy N. Anaso, Emeka S. Fidelis (2024d). Haematological profile and fertility potential of rabbits supplemented with Camel's Foot (Piliostigma thonningii) essential oil-based diet. Turkish Journal of Agriculture - Food Science and Technology, 12(12): 2470-2477, 2024. DOI: https://doi.org/10.24925/turjaf.v12i12.2470-2477.6870

Anaso, E.U., Salihu A.M. (2025). Identification and Antimicrobial Susceptibility of Pseudomonas aeruginosa strain PAO1 Isolated from African Catfish skin Scrapings. Science Letters 2024;13(1):1324350sl. DOI:https://doi.org/10.47262/SL/13.1.132024350

Benchaar, C., Calsamiglia, S., Chaves, A. V., Fraser, G. R., Colombatto, D., McAllister, T. A., & Beauchemin, K. A. (2008). A review of plant-derived essential oils in ruminant nutrition and production. Animal Feed Science and Technology, 145(1–4), 209–228. https://doi.org/10.1016/j.anifeedsci.2007.04.014

Calsamiglia, S., Busquet, M., Cardozo, P. W., Castillejos, L., & Ferret, A. (2007). Essential oils as modifiers of rumen microbial fermentation.

Journal of Dairy Science, 90(6), 2580–2595. https://doi.org/10.3168/jds.2006-644

Devendra, C. (2011). Integrated tree crops–ruminants systems in South East Asia: Advances in productivity enhancement and environmental sustainability. Asian-Australasian Journal of Animal Sciences, 24(5), 587–602. https://doi.org/10.5713/ajas.2011.10213

FAO. (2022). World livestock: Transforming the livestock sector through the Sustainable Development Goals. Food and Agriculture Organization of the United Nations.

Greathead, H. (2003). Plants and plant extracts for improving animal productivity. Proceedings of the Nutrition Society, 62(2), 279–290. https://doi.org/10.1079/PNS2002197

Makkar, H. P. S. (2018). Feed demand landscape and implications of food–feed competition. Animal, 12(8), 1742–1750. https://doi.org/10.1017/S175173111700324X

Makkar, H. P. S., & Ankers, P. (2014). Towards sustainable animal diets: A survey-based study. Animal Feed Science and Technology, 198, 309–322. https://doi.org/10.1016/j.anifeedsci.2014.09.018

Olafadehan, O.A., Anaso, E.U., Shoyombo, A.J., Okunade, S.A. (2023a). Body thermoregulation and serum metabolic profile of Kano Brown bucks fed Pleurotus ostreatus biodegraded sugarcane scrapings. Biotechnology in Animal Husbandry, 39(1), 61-72. 37 https://doi.org/10.2298/BAH2202081R

Olafadehan, O.A., Gero, A., Okunade, S.A., Kholif, A.E., Adewuyi, P.A., Shoyombo, A.J., Anaso, E.U., Onwih, E.E. (2023b). Partial substitution of concentrate with Parkia biglobosa foliage improves feed utilization and performance of goats. Archiva Zootechnica, 26(2), 83-95. DOI: 10.2478/azibna-2023-0016.

Patra, A. K. (2011). Effects of essential oils on rumen fermentation, microbial ecology, and ruminant production. Asian Journal of Animal and Veterinary Advances, 6(5), 416–428. https://doi.org/10.3923/ajava.2011.416.428

Patra, A. K., & Saxena, J. (2011). Exploitation of dietary tannins to improve rumen metabolism and ruminant nutrition. Journal of the Science of Food and Agriculture, 91(1), 24–37. https://doi.org/10.1002/jsfa.4152

Patra, A. K., & Yu, Z. (2012). Effects of essential oils on methane production and fermentation by rumen microbes. Applied and Environmental Microbiology, 78(12), 4271–4280. https://doi.org/10.1128/AEM.00309-12

Windisch, W., Schedle, K., Plitzner, C., & Kroismayr, A. (2008). Use of phytogenic products as feed additives for swine and poultry. Journal of Animal Science, 86(14_suppl), E140–E148. https://doi.org/10.2527/jas.2007-0459

CHAPTER 4
PROMOTING COCOA FARMING FOR ENHANCED FARMERS' WELLBEING IN NIGERIA

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INTRODUCTION

Cocoa (Theobroma cacao) before independence and discovery of crude oil, was Nigeria's major foreign exchange earner around which major development projects were planned. Cocoa farming became very important after independence, highly employing and raising social status of the cocoa workers in the cocoa farming communities. Nigeria ranks fourth in the world in terms of cocoa exports, behind Ghana, Indonesia, and Cote d'Ivoire. According to Afolayan (2020), Nigeria produces 300–350 metric tons of cocoa annually, the majority of which is exported. The Nation sells 96% of its cocoa production.

Cocoa is a significant economic crop in Nigeria because apart from giving farmers employment and income, it supplies raw materials for industry, and generates foreign exchange for the Nation. Olowolaju (2014) asserts that cocoa is a significant supply of raw materials and a source of income for the Governments of the States that produce cocoa in Nigeria. As the biggest source of non-foreign exchange earnings in Nigeria, cocoa employs millions of Nigerians as growers, processors, licensed buying agents, marketers, and exporters, contributing significantly to their household income. Additionally, this cash crop has made significant contributions to the nation's GDP through high foreign exchange rates, rural economic growth, and increased farmer income in the fight against poverty (Fountain and Huetz-Adams, 2018, Agbota, 2013).

However, the cocoa sub-sector saw a downturn when the oil boom of the 1970s arrived. Olaiya (2016) even observed that the oil boom syndrome in conjunction with other socioeconomic reasons was the reason behind the decrease in cocoa production. Following this development, other institutional initiatives were implemented by the Federal Government of Nigeria, including the deregulation of the cocoa trade, the implementation of a rehabilitation program for cocoa, the delivery of better cocoa varieties to farmers at subsidized rates, and a limited number of new plantings from the mid-1980s through the majority of the 1990s. The production of cocoa increased somewhat as a result of this endeavor (Adebiyi and Okunlola, 2013). Although production rose to 230,000 tons in 2017, it fell short of the former production volume, as acknowledged by Akintelu et al. (2019).

The country lost the expected monetary value from foreign exchange, as evidenced by the drop, in cocoa output rate relative to expectations. Planting hybrid cocoa varieties, weed control (cultural maintenance), applying fertilizer, controlling capsids with insecticides, controlling black pod disease with fungicides, controlling weeds with herbicides, and fermentation and drying are some of the improved technologies used in cocoa production (Akintelu et al., 2019). In addition, the use of technology in Integrated Pest Management (IPM) is helping farmers live better lives. IPM can assist farmers in achieving both financial and health benefits in terms of increased output and income (Awoyemi and Aderinoye-Abdulwahab, 2019). Nonetheless, Essiet (2018) noted that further technological utilization is necessary to maximize production and quality of cocoa. Better farming methods and post-harvest procedures will also improve yields and improve cocoa quality (Aikpokpodion, 2014).

Concepts of wellbeing have gained prominence in recent years as a result of intricate policy, intellectual, and cultural discussions around how to measure and define wellbeing as a means of tracking social progress and informing public policy, which is customary in developed democracies across the globe. Long-standing philosophical, sociological, psychological, and economic viewpoints on the happy life are incorporated into these discussions (Vernon, 2014). The eudaimonic approach, which stresses human flourishing and healthy psychological functioning, and the hedonic perspective, which promotes happiness, positive affect, and life satisfaction, have historically been the focus of wellbeing research. However, there are still broad, overlapping, and hazy definitions of wellbeing depending on the discipline or policy perspective being used (Mansfield, Daykin & Kay, 2020). Nevertheless, there is a relationship between the utilization of improved technologies in cocoa farming and the wellbeing of farmers in Nigeria. It is clear that raising cocoa sector production is essential to raising rural residents' quality of living. Nigeria has a comparative advantage in producing and exporting cocoa, it is anticipated that the country would become the world's top producer of cocoa by increasing its production through the use of improved technologies. The well-being status of cocoa farming households may fluctuate or remain constant as a result of changes in their means of subsistence brought about by adjustments in income and expenses (Lawal et al., 2015).

Smallholder farmers primarily make their living from the production of cocoa no doubt, therefore any changes in this sector will inevitably affect their ability to support themselves (Akinwale, Ojerinde, and Owoade, 2019). It is a fact that a person's social contact and involvement with others as well as their need for a sufficient income to meet basic necessities are all aspects of their well-being.

The Nigerian Cocoa Research Institute (CRIN) has developed a number of technological advancements and improvements that may lessen the difficulties Nigerian cocoa farmers encounter in growing and processing cocoa. The technologies that are essentially production-focused are meant to assist farmers in increasing their yields. Improved seedlings, recommended fertilizer rates and applications, recommended herbicide and pesticide rates and applications, and enhanced management technologies are some of these production technologies. However, the better yield from improved technology utilization may translate into a very low price because extension staff members do not provide enough marketing information needed by farmers to know when, how and where to sell their cocoa beans and make good money.

The goal of all these enhanced cocoa production technologies being made available to farmers is to raise the standard of living for thousands of rural households that primarily rely on cocoa farming by increasing yield per hectare, which will raise income and enhance the social, psychological, and economic well-being of these households.

As a result, the Chapter discusses the contributions of cocoa farming to the economy, its challenges and how cocoa farming can be promoted to enhance the wellbeing of farmers in Nigeria.

1. THE EARLY YEARS OF COCOA FARMING IN NIGERIA

The foundation for cocoa cultivation in West Africa was laid by the transport of Amelonado cocoa from Brazil to Saotome in 1855, and then to Ghana and Nigeria later in the century (Verter and Becvafova, 2014). However, in the second part of the nineteenth century, America lost its lead in the World's cocoa output, and Africa took over.

Eduardo and Philippe (2013) claimed that Africa still holds this position now. Around 70% of global production, which varies annually due to climate fluctuations, comes from West Africa, making it a major producer (Abayomi, 2017). First planted in the Delta, later cocoa made its way north to Western Nigeria's ideal cocoa belt. The primary cocoa-producing countries at the moment are Cote D'Ivoire, Ghana, Indonesia, and Nigeria, according to the International Cocoa Organization (2019).

The Ivory Coast, Ghana, Nigeria, and Cameroon are the four main West African producers of cocoa, and collectively they produce nearly two thirds of the world's cocoa, according to the International Cocoa Organization (ICCO) (2017). With a 340, 163 tonne production capacity, Nigeria ranks fourth in Africa after Ghana, Cameroon, and Côte d'Ivoire. The main cocoa-producing nations outside of West Africa are the Dominican Republic, Ecuador, Brazil, Malaysia, and Indonesia. Indeed, seventy percent of global supply of cocoa came from Africa.

Since 1904, Nigeria has gained more and more recognition as a producer of cocoa. The country's top growing regions for cocoa are the western states of Ondo, Ekiti, Ogun, and Oyo, as well as the south-south areas of Edo State, Ikom in Akwa Ibom State, and Cross River State. Large cocoa plantations are primarily located in Nigeria's southwest. However, with 640 000 hectares of cultivated area, cocoa is currently produced in fourteen states in Nigeria. In these 14 states—Abia, Adamawa, Akwa Ibom, Delta, Edo, Ekiti, Kogi, Kwara, Ogun, Ondo, Osun, Oyo, and Taraba—more than 200,000 rural households primarily rely on cocoa as a source of income. Moreover, cocoa continues to be the leading employer of labour in the nation and the second-biggest source of foreign cash earnings after oil.

The "business" of cocoa (cultivation and/or processing) now includes three additional states in addition to the previously stated fourteen. Considering that Lagos and Imo States are processors and Bayelsa State, one of the three, is a major producer of cocoa, given that all of the plantations that were photographed were large-scale holdings (Akintelu, Mele, Sobanke and Adewunmi, 2019; Lawal, Omonona, Oluwatayo, Oyekale and Salman, 2015; FAO, 2013).

2. CONTRIBUTIONS OF COCOA FARMING TO NIGERIAN ECONOMY

Nigeria's primary agricultural export is cocoa, which contributes 0.3% of the country's agricultural GDP (FAO, 2013). In the first quarter of 2022, Nigeria's earnings from exports accounted for around 41.6% of its foreign exchange earnings, which came from raw cocoa beans, which brought in N122.9 billion (Agency Report, 2022).

The primary agricultural subsector that significantly boosts Nigeria's GDP is cocoa, which also accounted for 15% of all exports from the country in 1970 (Adebile and Amusan, 2011). Prior to its independence and the discovery of crude oil, Nigeria's main source of foreign cash earnings from which large-scale development initiatives were centered (Ukoha and Nwachukwu, 2015) was cocoa. Similarly, the Guardian Newspaper (2010) confirmed that, after crude oil, cocoa continues to be the nation's second-highest foreign earner and, as such, demands significant attention.

Following independence, cocoa growing gained significant importance, creating high-paying jobs and elevating the social standing of cocoa workers in the cocoa-growing towns. Then, Nigeria's infrastructure and human resource development were funded by the proceeds from the sale of cocoa.

The growth of an independent economy was aided by the growing sales of food commodities grown either beside or in addition to cocoa. The governments of the States that produce cocoa rely on cocoa as a significant source of income and raw materials (Olowolaju, 2014). Millions of people who live and work in the cocoa belt are significantly impacted. Worldwide, cocoa is a significant product that is both a cash crop for nations who grow it and an essential import for those that process and consume it. The production of cocoa is one of the businesses that encourages income growth and distribution and increases the revenue of low-income households, all of which are likely to contribute to the elimination of poverty.

In a study by Oseni and Adams (2013) on the cost-benefit analysis of certified cocoa production in Ondo State, Nigeria, the profit, gross margin, net present value (NPV), benefit cost ratio (BCR), and internal rate of return (IRR) of N14, 889,098, N20,238,090, N5,253,237,1.45, and 59.64%, respectively, indicated that conventional cocoa production is profitable.

The socio-economic characteristics of registered cocoa farmers in Edo State, Nigeria, were studied by Osarenren, Ejuetueyin, and Eweka (2016); a budgetary technique was used to determine the profitability of cocoa production, and it was found to be profitable in the study area at a gross margin of N66, 350, net farm income of N59, 200, and net return on investment of N 1.11. Then, since the gross ratio (GR) of cocoa production is 0.47 and the benefit cost ratio (BCR) is more than 1, the expense structure ratio and benefit cost ratio of 2.11 and 0.12, respectively, showed that cocoa production was economically profitable and viable. These profitability ratios demonstrate that the production of cocoa is a lucrative industry in the research region.

A Cost and Return Analysis of Three Cocoa Production Management Systems in the Cross River State Cocoa Belt, another study by Nkang, Ajah, Abang, and Ede (2007) on investment in cocoa production in Nigeria, concluded that cocoa production is a profitable business regardless of management system because all of them had positive net present values (NPV) at a 10% discount rate. Farms under lease have the highest net present value. For all three management systems, the benefit-cost ratio (BCR) at a 10% discount rate was larger than unity, indicating high returns on cocoa production. Farms under owner management had the greatest BCR, followed in that order by farms under lease management. With their high net present values (NPVs), farms under lease management were more profitable than those under alternative management schemes.

Additionally, Oladoyin and Aturamu (2022) conducted a second study on the cost-benefit analysis of cocoa production in Ondo State, Nigeria's Idanre Local Government Area. The cost-benefit analysis's conclusion indicated that cocoa production was profitable at an interest rate of 20°k. Additionally, a 4.48 benefit-cost ratio was found, meaning that for every N1 invested in the production of cocoa, a profit of N3.48 kobo was made. This suggests that cocoa farming is a profitable enterprise in Nigeria; this is in agreement with a study conducted by Ukoha et al (2025) on the cost and returns of utilizing improved cocoa production technologies by farmers in Cross River and Akwa Ibom States, Nigeria, indicating that cocoa farmers in both States at breakeven in the enterprise.

3. CHALLENGES OF COCOA FARMING IN NIGERIA

Cocoa was the nation's main source of foreign cash between 1950 and 1960. Cocoa was pushed to the second rank in terms of the nation's foreign exchange revenues after oil was discovered in 1970 and other socioeconomic variables. Since then, the Nigerian economy has revolved around the oil sector, resulting in poverty, unemployment and an inadequate industrial foundation.

Prior to the discovery of "black gold," or crude oil, cocoa was Nigeria's main cash crop and export, particularly in the country's south (Afolayan, 2020). The production of cocoa fell globally, from 4.3 million metric tonnes in 2010/2011 to 4.0 million metric tonnes in 2011/2012 and 3.9 million metric tonnes in 2012/2013, according to data published by the International Cocoa Organization (ICCO, 2019). The following season saw a rise to 4.37 million metric tons, a decline to 3.97 million metric tonnes in 2015–2016, and subsequent seasons have seen a rise above the 4 million metric tonnes threshold.

Furthermore, Afolayan (2020) noted that although cocoa production has grown rapidly and had a positive impact on the country's economy, the percentage of the population engaged in agriculture has decreased dramatically since Nigeria discovered crude oil in commercial quantities. A number of risks and uncertainties, including weather, pest and disease attacks, and cocoa price volatility on the international market, have been identified as the main causes of the drop in production (ICCO, 2019).

Continuing, Samuel (2017), observed that issues such as; low fertility, climate change, global price fluctuation, insufficient processing firms and inadequate access to production inputs such as fertilizers are posing great challenges toward sustainable cocoa production in Nigeria. Other factors that made production to dwindle over time included ageing cocoa trees, old age of farmers, poor agricultural practices and climate change. Also, identified as challenges to cocoa to production in Nigeria were; low yields, inconsistent production patterns, disease incidence, pest attack and little agricultural mechanization.

According to additional research, the Sector started to decline because of a general disregard for the agricultural output brought on by the oil boom in the 1970s.

This also contributed to a decline in the subsector's fortunes and the income of about 2.5 million small-holder cocoa farming families (Ayodele, Oduntan and Okuraye, 2019; Oreyemi, Sanusi, Okojie, Olaiya and Akerele, 2015).Afolayan (2020) went on to say that since the 1970s, crude oil has continued to be the biggest source of foreign exchange profits, while cocoa—a flexible, sustainable, and renewable source of income—hasn't yet recovered its former prominence. However, the primary reasons for Nigerian farmers' incapacity to produce cocoa like those in Ghana and Côte d'Ivoire include old plantations, fluctuations in global prices, loss of soil fertility and the government's disregard for agriculture in favor of crude oil.

Another notable challenge to cocoa farming is that the majority of low-income, small-scale, and unskilled farmers in Nigeria produce cocoa; they don't employ manure or fertilizer to increase soil fertility (Ukoha, 2011). This was equally noticed by Ajayi and Adeoti (2019), that smallholders with extremely low productivity levels dominate the cocoa industry. Major barriers to productivity include disease and pest assaults, dwindling soil fertility, poor agronomic practices, the use of low-yielding varieties, restricted credit availability, and inadequate infrastructure (Ajayi and Adeoti, 2019).

Also, due to the issue of poor management practices used by cocoa farmers, there has been a decrease in cocoa production and unpredictability in its output (Awoyemi and Aderinoye-Abdulwahab, 2019). Additionally, the dwindling productivity of the country's ancient cocoa trees slows down the production of cocoa in Nigeria. According to Essiet (2014), bugs and illnesses caused farmers to lose anywhere from 30% to 100% of their cocoa harvest. Crop productivity and income have also decreased due to a lack of improved seeds and planting supplies, low-yielding old trees, and a lack of information about new and more effective agricultural techniques, among other factors. According to Farm Gate Foundation (FGF) (2017), small-holder cocoa farmers have significant barriers to entering the chocolate market and participating in other value chains because of factors like inconsistent annual production amounts, poor bean quality, or lack of storage facilities.

Processing and exporting their produce present difficulties for the farmers as well as low demand caused by high transportation costs, lack of market knowledge, and the inability to satisfy prospective customers' accepted standards and certification requirements. Furthermore, Oreyemi, Sanusi, Okojie, Olaiya, and Akerele (2015) concurred that the cocoa industry is exceedingly hazardous, resulting in price speculation with unfavorable outcomes like improperly dried beans, which deter farmers from investing in cocoa farms due to price volatility.

This is due to the fact that farmers are more vulnerable to unstable and unpredictable revenue due to price volatility. As a result, the majority of farmers have income risk, which puts them at danger of receiving little or no revenue.

4. MEASURES PUT UP BY NIGERIAN GOVERNMENT TO BOOST COCOA FARMING

The Federal Government of Nigeria developed a number of initiatives to support the revival of cocoa cultivation, processing, and marketing in the Country, indicating that the improvement of cocoa farming techniques has been at the forefront of numerous sector interventions in recent years (Fountain and Huetz-Adams, 2018). In order to oversee the Cocoa Development Program across Nigeria's 14 producing States, the National Cocoa Development Committee was established in the year 2000. The long-term goal of the program was to assist with the restoration of 15,000 hectares of cocoa plantations annually in order to reach an annual production level of one million metric tons by 2010. To counteract the impacts of aging cocoa plantations in Nigeria, producers were thus encouraged to replant with improved/disease resistant varieties, various agrochemicals, and other inputs. Enhancing the income of cocoa farmers and diversifying foreign exchange revenues through increased cocoa production are two of the specific goals (FAO, 2013).

In the same way, the Fertilizer Policy was another example of a Federal Government intervention in the Cocoa Industry. In addition to Input Support Programs specifically targeted at the Cocoa Industry, there are other measures that impact cocoa production, albeit it is impossible to pinpoint their precise impact.

Farmers can receive input help in the form of fertilizer from the Federal and State Governments. But the amount of contribution differs yearly and from State to State in a consistent manner. Under the Federal Market Stabilization Programme (FMSP) of 1999–2011, businesses were permitted to manufacture, import, and distribute fertilizer to State Governments at a 25 percent subsidy. State governments also have the option to increase the subsidy (FAO, 2013).

The Cocoa Research Institute of Nigeria (CRIN), established in Ibadan, Oyo state, on December 1, 1964 by the Federal Government of Nigeria, to make contributions to cocoa improvement along the value chain and research needs, providing farmers with enhanced, disease-resistant, and high-yielding cultivars; educating growers on contemporary agricultural techniques and business development techniques (CRIN Publication, 2016).

In addition, Lawal, Omonona, Oluwatayo, Oyekale, and Salman (2015) noted that CRIN assists with research needs and crop development along the value chain, providing farmers with improved, high-yielding varieties that are resistant to disease and training growers in contemporary agricultural techniques and business development skills. Similarly, Adebiyi and Okunlola (2013) pointed out that CRIN created a number of rehabilitation methods with the aim of revitalizing ancient cocoa trees on Nigerian cocoa plantations. such as coppicing and grafting, selective tree replanting, coupon regeneration, planting beneath old cocoa trees, and complete or phased farm replanting.

The National Development Economic Team introduced the Agricultural Transformation Agenda (ATA) plan of 2013 in 2012 with the goal of establishing sustainable agriculture and agribusiness in Nigeria to increase the income of rural farmers (Adesina, 2014). The agenda's main objectives are to establish agriculture as a business, encourage private sector investment in the industry, support the creation of marketing groups with a focus on the private sector, and advance incentive-based risk sharing for agricultural lending (NIRSAL). According to Adesiyan, Adesiyan, and Agbonlahor (2019), CRIN released eight new cocoa hybrids through the Agricultural Transformation Agenda (ATA), providing farmers in the nation's cocoa-producing states with 1.4 million cocoa pods in addition to inputs like fertilizers, fungicides, and insecticides at a subsidized rate to the farmers.

This is because cocoa is one of the capital-intensive businesses especially when it comes to the purchase of improved seedlings. Similar to this, ICRISAT (2020) noted that ATA received funding for a project from the Africa Development Bank. ATA's single goals are to increase access for farmers and other value chain participants to financial services and markets, decrease post-harvest losses, add value to local agricultural produce, and develop rural infrastructure. A national commodity-specific transformation strategy is envisioned for cocoa, along with cassava, sorghum, rice, and cotton, especially in the Southern States (FAO, 2013).

A key component of ATA is the 2013 Cocoa Transformation Agenda (CTA). This program was implemented in Nigeria in 2011 with the goal of eliminating hunger through the development of an agricultural sector that generates revenue growth and positions Nigeria as a major player in the world's food markets driven by cocoa. The specific or primary objective of the Cocoa Transformation Agenda, according to FAO (2013), is to quickly enhance Nigeria's cocoa bean production by a combination strategy of increased productivity and planting newer (and producing) trees. In particular, the plan called for the creation of new plantations through a Cocoa Development Fund and the 30% expansion of current cocoa plants through the Seeds Multiplication Program. Furthermore, the Development of the Transformation Agenda mandated the use of customized fertilizer blends for cocoa to increase yields quickly, up to 600 kg per hectare.

Aikpokpodion (2014) went on to discuss additional advantages of the program, such as creating a database of cocoa farmers' complete biometric data to facilitate the better distribution of hybrid seeds (which are predicted to mature in two years as opposed to four or five years), fertilizers, and other agrochemicals to farmers. This is on top of farm upkeep, historic plantation repair, and expansion initiatives utilizing excellent agricultural methods and intensification. As of 2013, cocoa producers had received around 790,000 hybrid pods at no cost as part of the CTA (Aikpokpodion, 2014).

5. COCOA FARMING AND FARMERS' WELLBEING IN NIGERIA

According to Adelodun (2017), small-scale farmers in Nigeria who plant cocoa on less than 5 hectares account for 80% of the country's cocoa production. Less than 300 kg of cocoa are produced annually per farmer on average. According to research, the majority of cocoa farmers—more than 70%—are smallholders who reside in rural areas where they struggle with extreme poverty and inequality, use antiquated tools and technology, lack access to social amenities like hospitals, schools, piped water, and electricity, and make very little money (Agwu et al., 2014). Therefore, it is still possible to argue that smallholder farmers primarily make their living from the production of cocoa, and any changes to this crop will inevitably have a negative impact on their way of life.

It is also quite concerning that those smallholders with extremely poor productivity levels dominate the cocoa industry with the use of low-yielding varieties, disease and pest infestations, dwindling soil fertility, poor agronomic practices, restricted credit availability, and inadequate infrastructure as the main factors limiting productivity (Ajayi and Adeoti, 2019). Obike et al. (2017) also noted that although cocoa is a major source of income and the main source of subsistence for the majority of Nigerian rural farmers, it is still largely managed by smallholders with little use of inputs or productivity-enhancing agricultural techniques. In a similar vein, farmers cultivate cocoa on small plots of land—not more than two hectares—which is obviously insufficient to yield larger profits because they use antiquated techniques rather than automated ways (Ukoha and Nwachukwu, 2015). Additionally, these farmers have lost a significant portion of their alleged income due to cocoa merchandise preying on them and taking undue advantage of the farmers' ignorance of market information regarding when, how, and where to package and sell their products. According to Essiet (2014), if cocoa farmers don't know how much other marketplaces outside of their villages are ready to pay, they won't have much chance of receiving a fair price for their produce.

He acknowledged that farmers receive meager compensation for the cocoa they harvest, carry heavy loads, clear their field with machetes, and breathe in dangerous pesticides (certain chemicals have been linked to cancer, liver and renal problems, headaches, nausea, and diarrhea) as part of their regular work schedule.

In deed numerous issues have plagued the cocoa industry in Nigeria, and farmers have suffered as a result of the lack of increased revenue from the industry resulting from the earlier stated challenges be delving cocoa farming. This has had a significant impact on the general well-being and income of rural households whose sole source of income is the revenue from cocoa farming. The insufficiency of proficient service providers to educate and raise the awareness of smallholder cocoa farmers and enhance their farming business acumen is another issue. Because cocoa farming is the primary source of income for these farmers, it has a direct impact on their well-being. Their happiness and satisfaction with the profits from their cocoa farming enterprise have diminished.

Wellbeing can be seen as a person's overall sense of well-being, including their overall feelings, social and personal functioning, and overall life evaluation. It is the middle ground between a person's available resources and the difficulties they encounter. It also refers to the state in which one is both happy and content, experiencing positive emotions like happiness and contentment, and realizing one's potential, taking charge of one's life, feeling purposeful, and forming meaningful relationships. Three basic dimensions (3Ds) comprise what people have (objective), what they can do (relational), and how they feel about what they have and can accomplish (subjective), which together comprise wellbeing (Huppert, 2017).

According to Huppert (2017), the term "wellbeing" is used interchangeably to refer to a broad variety of ideas, such as resilience, self-efficacy, self-determination, self-esteem, quality of life, mood enhancement, positive mental health, and worthiness. Two categories of elements influence well-being, according to Sabillion et al. (2022): an individual's life-ability, or capacity to cope with life, and the liveability, or favorable qualities of their social and natural surroundings.

Nonetheless, the three aspects of the farmers' wellbeing which can be influenced by their activities in cocoa farming as discussed here include the social, psychological and economic wellbeing. A condition of social wellbeing is one in which everyone's basic needs are satisfied and they may live in harmony with one another in communities that offer chances for growth. The hedonic perspective of psychological well-being views it as a blend of positive emotional experiences like happiness and the eudaimonic perspective of optimally effective functioning in one's personal and social life. International Rescue Committee (2023) defines economic wellbeing, on the other hand, as having assets and a stable source of income in addition to meeting one's most basic survival needs. Therefore, a holistic approach to all three aspects of wellbeing is very necessary to achieve a good standard of living for the cocoa farmers.

Being content and happy is ultimately the one thing that people always look forward to. All people strive to maximize a measurable degree of happiness. Happiness and pleasure are the cornerstones of wellbeing. It is anticipated that using the enhanced cocoa production technologies created by CRIN for farmers and implementing the recommendations of this study will not only greatly boost cocoa farming in terms of output; it will raise income, lower poverty, guarantee satisfaction, and enhance the general well-being of the cocoa farmers in Nigeria. Indeed, there's a strong correlation between increase in cocoa farmers' income and their psychological, economic and social wellbeing (Ukoha et al, 2024).

CONCLUSION

No doubt, there are steps the Federal Government of Nigeria has already taken to address the challenges faced by cocoa farmers in order to boost production that will in turn enhance the farmers' wellbeing, there are other critical and salient areas that need to be looked into. Global, national, and local players must act quickly to boost cocoa production output through creative means and reduce these challenges in order improve the wellbeing of farmers as well as combat poverty and hunger in Nigeria.

These include:

- Curbing the activities of 'middle men' that reap the profit of the poor cocoa farmers. Government should come up with policies that will combat this.
- Cocoa farmers should be encouraged to form strong Cooperative Societies so as to get a better bargain of their produce at the point of sale
- Government needs to ensure a reliable cocoa market by introducing a cocoa quality improvement and branding instrument that will save cocoa from being sold at a discount in World market.
- There's also need to structure the commodity chain from a socioeconomic perspective, particularly in light of the recent liberalization that has led to the withdrawal of the State and increased involvement of private companies.
- Extension agencies should train farmers on how to improve cocoa production sustainability through adapted varieties and cost-effective crop management techniques like replanting.
- Government at all levels should assist farmers to reduce parasite pressure, which is a major factor limiting cocoa production and control quality to meet a wider range of customer requirements.
- Extension agencies should provide marketing information and linkages to get farmers informed and updated on when, where and how to market their bumper cocoa produce so as to earn more income for increased wellbeing status.
- Government should assist cocoa farmers boost production by granting them loan and subsidies on agro chemicals, spraying equipment, artificial dryers etc. and these properly channeled to the farmers.
- High taxation on cocoa beans is a serious constraint to the cocoa farming enterprise in Nigeria; hence Government needs to reduce the heavy load of taxation borne by cocoa farmers in the course of marketing their produce as exporters transfer the high tax to them.
- Federal Government can put in place price regulatory mechanism by reintroducing Cocoa Marketing Board to reduce the loss of income that farmers sustain due to cocoa bean price fluctuation. This will enhance their economic wellbeing.

REFERENCES

Abayomi, A. (2017). Cocoa Production in Nigeria: A Literature Review. Analysis, Food and Agribusiness (accessed from www.cpparesearch.org, 11/06/19).

Adebile, O.A. and Amusan A.S. (2011). The Non-Oil sector and the Nigeria Economy. A case Study of Cocoa Export Since 1960. International Journal of Asian Social Science. 9 (1), 142-151

Adebiyi, S. and Okunlola, J. O. (2013). Factors Affecting Adoption of Cocoa Farm Rehabilitation Techniques in Oyo State of Nigeria. World Journal of Agricultural Sciences, 9 (3): 258-265, 2013 ISSN 1817-3047

Adelodun A., (2017). Cocoa production in Nigeria: A literature review Accessed on April 7,20182018.http://cpparesearch.org/nu-en-pl/cocoa-production-innigeria

Adesina, A. (2014). Non-oil earnings: Federal Government targets $1.3bn from Cocoa. An address presented at the Cocoa Summit in Abuja. Administration Vol.1: Office of the Special Adviser to the President on Research Documentation and Strategy

Adesiyan O. F., Adesiyan A. T. and Agbonlahor M. (2019). Adoption of cocoa input technologies under agricultural transformation agenda among women cocoa farmers in Ile-Ife, Osun State. Journal of Development and Agricultural Economics.11(3), 52-56

Afolayan, O. S. (2020). Cocoa Production Pattern in Nigeria: The Missing Link in Regional Agro-Economic Development. Analele Universităţii din Oradea, Seria Geografie. 30(1), pp.88-96. https://doi.org/10.30892/auog.301110-815

Agbota, S. (2013): "Cocoa contributes $900m to Nigeria's economy in 2012 – BMI". The SUN Newspaper, July 15, 2013. www.sunnewsonline.com

Agency Report (2022). Nigeria earns N122.9bn from Cocoa Export. www.premiumtimes.comAgriexchange.apeda.gov.in/marketreport/Reports/Nigeria_cocoa _product NI11018

Aikpokpodion, P. (2014). Cocoa Production: Nigeria positions for better yields. Available online at www.agronigeria.com.ng/2014/13cocoa. Retrieved 24/02/2015

Ajayi, A. M. and Adeoti, S. O. (2019), Adoption of Improved Agricultural Technologies by Cocoa Farmer and Effects on Farm Income: Evidence from Ondo State, Nigeria, Journal of Agricultural and Rural Research, 3(4), 140-157.

Akintelu, S. O., Mele, L., Sobanke, V. O. and Adewunmi, M. (2019). Adoption of some cocoa production technologies by cocoa farmers in Kogi State, Nigeria. International Journal of Agriculture Innovation, Technology and Globalization, 1(1), 31 - 43

Awoyemi A.O. and Aderinoye-Abdulwahab S.A (2019). Assessment of the Use of Cocoa Production Management Practices among Cocoa Farmers in Ekiti State, Nigeria. Agro- Science - Journal of Tropical Agriculture, Food, Environment and Extension, 18 (2), 37- 41

Ayodele, O.V; Oduntan, O. and Okuraye, E.A. (2019). Adoption of Some Improved Technologies among Cocoa Farmers in Ifedore Local Government Area of Ondo State, Nigeria. Journal of Sustainable Technology, 10 (2), 1-9.

Eduardo, S., & Philippe, L. (2013). Successional Cocoa Agroforests of the Amazon- Orinoco-Guiana Shield. Forests, Trees and Livelihoods, 22 (1), 51-59

Essiet, D. (2018). How Nigeria can increase GDP with cocoa export http://thenationonlineng.net/how-nigeria-can-increase-gdp-with-cocoa-export/ (Assessed 23/02/2019)

Farm Gate Foundation (FGF) (2015). Sensitize and educate smallholders cocoa farmers Farm Gate Foundation (FGF) and World Cocoa Farmers Organization (WCFO) joint cocoa sustainability proposal project https://cocoa-alliance.org/wp- content//uploads/2017/10/Summery-Sensitize-Educate

Food and Agricultural Organization (FAO) (2013): Analysis of Incentives and Disincentives for Cocoa in Nigeria. www.fao.org/mafap

Fountain, A., and F. Huetz-Adams. (2018). "Cocoa Barometer 2018." http://www.cocoabarometer.org/Cocoa_Barometer/Download_files/2018 %20Cocoa%20Barometer%20180420.pdf. [Google Scholar]

Huppert, F. A. (2017). Challenges in defining and measuring well-being and their implications for policy. In Future directions in well-being (pp. 163–167). Cham: Springer.

International Cocoa Organization (ICCO) (2017) Quarterly Bulletin of Cocoa Statistic 2010/2016 [online] http://www.icco.org (accessed 2 November).

International Cocoa Organization (ICCO) (2019). Quarterly Bulletin of Cocoa Statistics, Vol. XLV - No. 2 - Cocoa year 2019

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) (2020). Agricultural Transformation Agenda Support Program-Phase 1(ATASP-1) – Nigeria – Sorghum. www.mel.cgiar.org

International Rescue Committee (2023). Where we focus Economic wellbeing. www.rescue.org

Lawal, J.O., Omonona, B.T., Oluwatayo, I. B., Oyekale, A.S., and K.K. Salman (2015). Welfare Transitions and Its Correlates among Cocoa Farming Households in Nigeria: An Application of Ordered Probit Approach. Selected Paper prepared for presentation at the 2015 Agricultural & Applied Economics Association and Western Agricultural Economics Association Annual Meeting, San Francisco, CA, July 26-28

Mansfield, Daykin & Kay, (2020). Leisure and wellbeing, Leisure Studies, 39:1, 1- 10, DOI: 10.1080/02614367.2020.1713195

Nkang, M. N, Ajah, E. A., Abang, S. O. and Ede, E. O. (2007). Investment in Cocoa Production in Nigeria: A Cost and Return Analysis of Three Cocoa Production Management Systems in the Cross River State Cocoa Belt. Journal of Central European Agriculture, 8 (1), 81-90

Obike, K. C., Ukoha, J.C.I. and Idu, M. A. (2017). Revolutionizing Cocoa Marketing: a Strategy for Promoting Cocoa Farming in Nigeria. Rivers State University of Science and Technology (RSUST), Department of Marketing Academic Proceedings, Rivers State. Pp. 67 – 72

Oladoyin, O. P. and Aturamu, O. A. (2022). Cost-benefit Analysis of Cocoa Production in ldanre Local Government Area of Ondo State, Nigeria. Asian Journal of Advanced Research and Reports,16(2),1-10

Olaiya, T.A. (2016) 'Examining the political-economy of cocoa exports in Nigeria', The International Journal of Applied Economics and Finance, 10 (1), 1–13.

Olowolaju, P. S. (2014). An Assessment of Investment in Technology in Cocoa Processing Industry in Nigeria. Journal of Economics and Sustainable Development, 5(10), 182 - 188

Oreyemi, A. B., Sanusi, R. A., Okojie, L. O., Olaiya, A. O. and Akerele, D. (2015). Produce Certification and Income Risk Management Strategies of Cocoa Farming Households in South-West Nigeria. Applied Studies in Agribusiness and Commerce - APSTRACT Centre, 9 (3), 75-87

Osarenren, C. O., Ejuetueyin, J. O. and Eweka, K. I. (2016). Socio-Economic Characteristics of Registered Cocoa Farmers in Edo State, Nigeria. Journal of Applied Scienced and Environmental Management, 20 (2), 261 –266

Sabillion, B. H., Gerster-Bentaya, M. and knielrim, A. (2022). Measuring farmers' well- being: Influence of farm-level factors on satisfaction with work and quality of life. Journal of Agricultural Economics, 73 (2), 452 -471

Samuel A. O., (2017). Problem and prospects of Cocoa production in Nigeria Economy: A review. International Journal of Social Sciences, 11 (2), 32 – 43

The Guardian Newspaper, Nigeria: (2010) "Agro Care" March 28, pp 67-68, 85

Ukoha, J. C. I. (2011). Adoption of Improved F3 Amazon Variety of Cocoa in Abia State, Nigeria. Unpublished M.Sc Thesis. Department of Agricultural Extension and Rural Development, Michael OKpara University of Agriculture, Umudike, Abia State, Nigeria.

Ukoha, J. C. I. and Nwachukwu I. (2015). Exploiting the Merits of Agricultural Transformation Agenda for Improved Cocoa Farming in Nigeria. In: Nwachukwu I., Ifenkwe, G. E., Onumadu F. N., Agbaraevo

M.N.B., Apu, U., Odoemelam L.E. and C. U. Nwobiala (eds) Book of Reading - Contemporary Issues in Agricultural Extension and Rural Development. Department of Agricultural Extension and Rural Development, Michael Okpara University of Agriculture, Umudike, Abia State, Nigeria. Pp. 362 – 368

Ukoha, J. C. I., Eze, S. O. and Odoemelam, L. E (2024). Assessment of psychological and social wellbeing status of Cocoa farming households in south-South zone, Nigeria. AKSU Journal of Agricultural Economics, Extension and Rural Development. 7(1): 65–79

Ukoha, J. C. L., Eze, S. O. and Kalu, U. (2025). Comparative Assessment of the Cost and Returns of Utilizing Improved Cocoa Production Technologies by Farmers in Cross River and Akwa Ibom States, Nigeria. Kebbi Journal of Agriculture and Natural Sciences. Volume 1, Issue 2: 271-278

Vernon, M. (2014). Wellbeing. London: Routledge.

Verter, N. and Becvafova, V. (2014), analysis of some Drivers of Cocoa Export in Nigerai in the Era of Trade Liberalization. Agris On-Line Papers in Economics and Information. 6 (4). 208 – 218

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