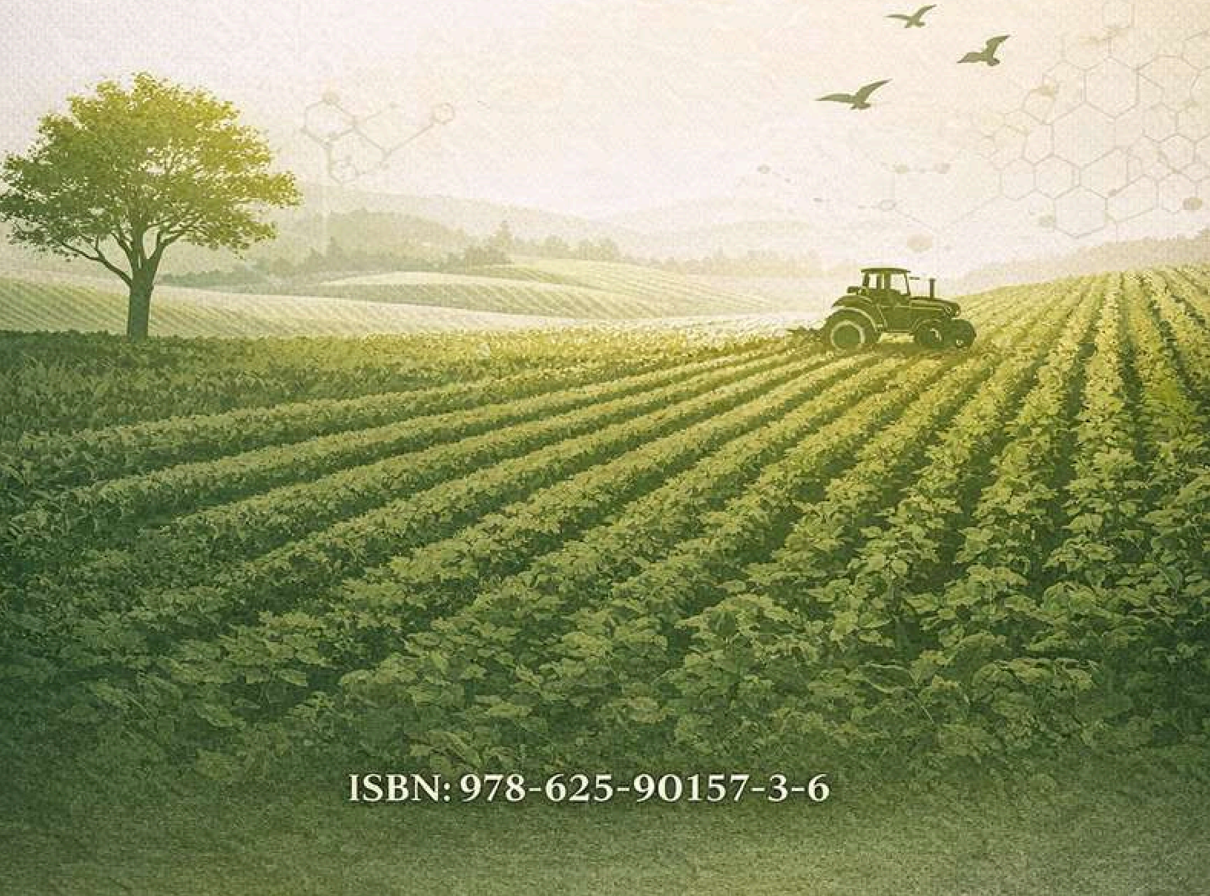
# CURRENT RESEARCH IN AGRICULTURAL PRODUCTIVITY AND ECOSYSTEMS



ISBN: 978-625-90157-3-6

# CURRENT RESEARCH IN AGRICULTURAL PRODUCTIVITY AND ECOSYSTEMS- 2026

**ISBN: 978-625-90157-3-6**
**DOI: 10.5281/zenodo.19485574**

April / 2026
Ankara / Türkiye

(The Licence Number of Publicator: 2014/31220)

E mail: info@ispecbooks.com

www.ispecbooks.com

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

ISPEC Publishing House – 2026©

ISBN: 978-625-90157-3-6

April / 2026

Ankara / Türkiye

# CURRENT RESEARCH IN AGRICULTURAL PRODUCTIVITY AND ECOSYSTEMS

**AUTHORS**

OLUSOLA MAKINDE Olubukola Olayemi
AROTUPIN Daniel Juwon
OLALEMI Adewale Oluwasogo
OLADEJO Babayemi Olawale
ADESIDA Iretioluwase Emmanuel
AKINFALA Esther Funmilayo
OYEWO Isaac. O. Jerry
OYEWO E.O
ADEOYE A. Samson
Fellyanus Haba ORA

# TABLE OF CONTENTS

# PREFACE

In an era marked by rapid population growth and unprecedented environmental challenges, the need for sustainable agricultural practices has never been more urgent. The global agricultural sector faces the dual mandate of increasing food production to ensure food security while minimizing its ecological footprint. This book aims to contribute to this critical scientific discourse by presenting contemporary research focused on innovative agronomy, sustainable land management, and the optimization of diverse agroecosystems.

The chapters compiled in this volume offer a deep dive into localized studies that carry broader implications for global agriculture. The research explores indigenous and improved alternative agronomic practices, specifically focusing on the proficiency of biofertilizers for soybean cultivation. Building on the foundation of soil health, the book also investigates the multidimensional effects of sustainable land management indicators on cassava productivity, providing essential insights for developing policies that support long-term environmental sustainability.

Furthermore, the collection addresses the vital role of livestock and pasture management within the agricultural landscape. By presenting a thorough evaluation of forage yield and quality in tropical natural pasture agroecosystems, the research underscores the necessity of maintaining balanced and productive grazing lands for sustainable animal husbandry.

We believe this comprehensive collection will serve as an inspiring resource for researchers, agronomists, policymakers, and students engaged in agricultural sciences. We extend our sincere gratitude to all the contributing authors for their rigorous research and dedication to the future of sustainable agriculture.

.

**Editorial Team**
**April 9, 2026**
**Türkiye**

# CHAPTER 1

# PROFICIENCY OF BRADYRHIZOBIUM JAPONICUM VIA CHARCOAL CARRIERS AS BIOFERTILIZER FOR SOYBEAN CULTIVATION: INDIGENOUS AND IMPROVED ALTERNATIVE AGRONOMY

[1]OLUSOLA-MAKINDE Olubukola Olayemi
[2]AROTUPIN Daniel Juwon
[3]OLALEMI Adewale Oluwasogo
[4]OLADEJO Babayemi Olawale
[5]ADESIDA Iretioluwase Emmanuel
[6]AKINFALA Esther Funmilayo

---

[1] Department of Microbiology, Federal University of Technology, Akure, ooolusola-makinde@futa.edu.ng, ORCID ID: 0000-0002-5012-2458

[2] Department of Microbiology, Federal University of Technology, Akure

[3] Department of Microbiology, Federal University of Technology, Akure

[4] Department of Microbiology, Federal University of Technology, Akure

[5] Department of Agricultural Extension and Communication Technology, Federal University of Technology, Akure

[6] Esther Funmilayo, Department of Microbiology, Federal University of Technology, Akure

## INTRODUCTION

Soybean (*Glycine max*) is a leguminous crop of immense agricultural and economic importance, primarily cultivated for its protein-rich seeds and oil content. It serves as a vital source of plant-based protein for human consumption, animal feeds and various industrial applications. The crops' economic importance is further amplified by its ability to enhance soil fertility through biological nitrogen fixation (BNF). Biological nitrogen fixation is a natural process where atmospheric nitrogen ($N_2$) is converted into ammonia ($NH_4^+$) by specialized microorganisms, primarily Rhizobia bacteria, living in symbiotic association with legume roots. This process significantly reduces the reliance on synthetic nitrogen fertilizers, which are energy intensive to produce, costly and can contribute to environmental pollution through nitrate leaching. However, many soils in Nigeria are deficient in native Rhizobia capable of forming effective symbiosis with soybean (Abaidoo *et al.,* 2007). The symbiotic relationship between soybean and *Bradyrhizobium japonicum* is crucial for optimal soybean growth and yield.

*Rhizobia* are Gram-negative bacteria which inhabit the root nodules of most leguminous crops. They are soil bacteria that fix nitrogen (diazotroph) after becoming established inside root nodules of legumes (Roychowdhury *et al*., 2015). There are several different genera of *Rhizobia*, all of them belong to the Rhizobiales, a probably-monophyletic group of proteobacteria and they are soil bacteria characterized by their unique ability to infect root hairs of legumes and induce effective nitrogen fixing nodules to form on the roots (Matiru *et al.*, 2004). These plants compounds induce the expression of nodulation genes in Rhizobia, which in turn produce lipochitooligosaccharide signals that trigger mitotic cell division in roots, leading to nodule formation (Lhuissier *et al.,* 2004).

The legume-Rhizobium symbiosis is a classic example of mutualism whereby Rhizobia supply ammonia or amino acids to the plant and in return receive organic acids as a carbon and energy source (Roychowdhury *et al.,* 2015). *Bradyrhizobium japonicum*, a slow-growing Rhizobia species, is widely used as a bioinoculant for enhancing nodulation and nitrogen fixation in soybean cultivation.

*B. japonicum* strains in agricultural soils can be highly variable, often insufficient to meet the nitrogen demands of high-yielding soybean varieties. This variability is influenced by several factors, including soil type, pH, organic matter content, temperature and the presence of antagonistic microorganisms.

To overcome these limitations, the application of microbial inoculants has become a standard practice in soybean cultivation in many regions. Inoculants are formulations containing specific, highly effective strains of Rhizobia that are introduced into the soil or directly onto seeds to enhance nodulation and nitrogen fixation. *B. japonicum* USDA110, in particular, is a well-characterized, efficient strain known for its nitrogen-fixing ability and compatibility with various soybean cultivars (Kaneko *et al.,* 2002). However, the success of Rhizobia inoculants in the field depends not only on the strain used but also on the carrier material that delivers and maintains the viability of the microorganism.

Traditional inoculant carriers such as peat have been extensively used due to their moisture retention, buffering capacity, and ability to support microbial survival. However, charcoal, a carbon-rich material derived from pyrolysed biomass, has gained attention as a potential alternative or supplementary carrier due to its high porosity, adsorptive capacity, and environmental availability in regions like Nigeria (Yanni *et al.,* 2001). Blending charcoal and peat as inoculant carriers may provide synergistic benefits, improving both microbial viability and plant growth-promoting potential.

Despite the availability of effective *Rhizobium* strains such as *B. japonicum* USDA 110, peat materials are mostly used as a carrier for *Rhizobia* but it is expensive due to its limited availability in Nigeria (Chao and Alexander, 1984). Charcoal is indigenous in Nigeria, its application as carriers of *B. japonicum* will be environmentally friendly and economically responsive. Developing cost-effective and sustainable carrier materials for Rhizobia inoculants will improve biofertilizer efficiency and promote sustainable soybean cultivation in Nigeria. Utilizing locally available materials like charcoal could reduce reliance on imported carriers and encourage local production of high-quality inoculants. This study, therefore, investigated the locally available and low-cost carriers like charcoal to determine their impact on inoculant efficiency and overall soybean performance.

This work aimed to assess the performance analysis of peat and charcoal-enhanced *B. japonicum* USDA 110 inoculants under controlled and field conditions using soybean as test crop.

## 1. MATERIALS AND METHODS

A pure strain of *B. japonicum* USDA110 and samples of peat were collected aseptically from the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria. The bacterial culture was transferred to the Microbiology Department of the Federal University of Technology, Akure. Upon collection, the strain was maintained on yeast mannitol agar (YMA) slant at 4°C for short term preservation. Prior to use, the culture was routinely sub-cultured and grown in yeast mannitol broth (YMB) to ensure purity, viability and sufficient inoculums density for the experimental procedures.

### Carriers for *B. japonicum*

Two carrier materials were utilized for inoculant formulation: peat and charcoal. The peat soil was sourced from IITA. Charcoal was obtained from wood residues, crushed into fine powder, and sieved to comparable particle size. Both carriers were sterilized by autoclaving prior to inoculation with *B. japonicum* USDA110 to eliminate contaminating microorganisms.

### *Plant materials*

Certified soybean (*Glycine max*) seeds of a locally adapted variety were used as host plants. The seeds were obtained from International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria.

## 1.1 METHODS

### *Phenotypic confirmation of B. japonicum USDA110 culture*

Distinct colonies of *B. japonicum* USDA110 culture from IITA were sub-cultured on sterile yeast mannitol salt agar and subjected to morphological and biochemical tests (Gram staining, catalase test, citrate utilization test, motility test and sugar fermentation test) as described by Cheesbrough (2006).

Bergey's manual of systematic bacteriology was employed to suggest the phenotypic characteristics of the bacterial isolates.

The confirmed bacteria were maintained on nutrient agar respectively, slanted at 4°C in refrigerator for subsequent use.

### *Production of Bradyrhizobium japonicum USDA110 iofertilizers*

### *Preparation of charcoal powder as B. japonicum USDA110 carrier*

Sixty grams of charcoal powder were weighed into polypropylene bags and then sealed. The bags were subjected to sterilization by autoclaving at 121°C for 30 minutes (Argal *et al.,* 2015).

### *Batch culture of Bradyrhizobium japonicum USDA110*

One loopful of the confirmed pure strain *B. japonicum* USDA110 was aseptically transferred to a 250ml flask containing 100ml of yeast mannitol broth. This was covered with a flamed cork and placed on a rotary shaker at 35°C for 7 days. This procedure was repeated for several other bottles.

### *Injection of B. japonicum USDA110 into Sterilized Carriers*

Yeast mannitol broth inoculated with *B. japonicum* was injected into the sterile charcoal powder and peat (positive control) bags individually. A 60:40 ratio mixture of carrier and inoculant was prepared by dispensing 40ml of inoculated broth into 60g of sterile charcoal powder / 60g of sterile peat) according to methods of Olusola-Makinde and Odamo (2019). The bags were gently and thoroughly massaged for homogeneity before being arranged in trays. The inoculants were then transferred into the incubator for curing (Paul *et al*., 2011).

### *Curing of inoculated B. japonicum USDA110 Carriers after Injection*

The inoculated carriers were subsequently arranged in trays and transferred into an incubator for curing. The inoculants were kept incubating for 15 days at the temperature of 28°C. This temperature is optimum for the growth of Bradyrhizobium japonicum USDA110.

During this conditioning period, the *Rhizobia* multiplied within the carrier material, thereby establishing a stable microbial population adapted to the substrate environment. Curing also helps to prevent the growth of the hyphae of fungi mycelium (Paul *et al.,* 2011). The use of controlled temperature and sterile conditions thus ensured that the carrier-based inoculant maintained a high density of viable Rhizobia cells, while preserving its integrity for subsequent application in soybean cultivation.

### *Application of Biofertilizer for Soybean Cultivation*

Loamy soil samples were gotten from Akure metropolis and subjected to sterilization by autoclaving at 121 °C for 30 minutes. After sterilization, the soils were allowed to cool before being transferred into planting pots, ensuring that the physical properties of the soil were not compromised during sterilization. This was done to kill all forms of live, including native Rhizobia to be able to estimate the efficacy of the product, the sterilized soil was shared into twelve planting pots.

Two varieties of soybean seeds; TGx 1951-3F and TGx 1904-6F were employed for planting experiment. The seeds are improved varieties developed by the International Institute of Tropical Agriculture (IITA), Nigeria. These varieties are noted for their adaptability to Nigerian agro-ecological zones.

Prior to sowing, soybean seeds were coated with biofertilizer using gum Arabic solution as an adhesive agent. This ensured uniform adherence of the peat or charcoal-based inoculants containing *B. japonicum* to the seed coat (Waclaw, 2022). Seeds without treatment with biofertilizer served as negative control, thereby providing a baseline for comparison of plant growth and nodulation against inoculated treatments (Lucas *et al.,* 2004).

Seeds were planted into sterilized soil filled pots under controlled growth conditions. Pots were arranged in a completely randomized design to minimize environmental bias and ensure the reliability of treatment comparisons. Watering was carried out uniformly across all treatments to maintain adequate soil moisture for seed germination and subsequent growth. Soil moisture was maintained close to field capacity to support proper nodulation while avoiding water logging conditions that could adversely affect plant root development and Rhizobial activity (Chiara *et al.,* 2019).

Growth conditions were carefully monitored throughout eight (8) weeks study period. Plants were maintained at an ambient temperature range of 25-

30°C, which is optimal for soybean growth in tropical environments. Relative humidity was maintained at approximately 60-70% to stimulate field conditions favourable to soybean. Natural light was supplemented, where necessary, to ensure a daily photoperiod of 12-14 hours, adequate for photosynthetic activity and reproductive development. Regular monitoring was performed to ensure that neither nutrient stress nor pest interference compromised the validity of the experiment (Bhuwan and Ratnesh, 2021).

All plants were allowed to grow under these conditions, and regular observations were carried out to monitor emergence, vegetative growth, flowering, and other growth-related parameters.

### *Growth and Nodulation Assessments*

The assessment of plant growth in soybean during the experimental period was conducted using standard morphological parameters that provide reliable indicators of vegetative development and physiological performance. These parameters included plant height, number of leaves, leaf length, leaf width and total plant length (Olusola-Makinde and Odamo, 2019).

### *Plant Height*

Plant height was measured from the base of the stem at the soil surface to the apex of the shoot using a calibrated ruler. This parameter is a widely accepted indicator of overall vegetative vigor and elongation response. An increase in plant height reflects the ability of the plant to utilize available nutrients, especially nitrogen, supplied through *Rhizobia* symbiosis, and to efficiently capture light for photosynthesis. Variations in height between treatments provided a direct measure of the impact of the different biofertilizer formulations.

### *Number of Leaves*

Leaf production was monitored by counting the fully expanded leaves on each plant. Leaf number is a critical determinant of photosynthetic capacity since each leaf represents an additional surface for light interception.

In soybean, nodulation efficiency and nitrogen fixation directly influence leaf proliferation, and hence this parameter served as a proxy for plant nutritional status and vigor. A higher number of leaves typically indicate improved growth conditions and greater potential for assimilate production.

### *Leaf Length and Leaf Width*

The dimensions of the leaves were assessed by measuring both length (from the base of the petiole to the tip of the lamina) and width (the widest point across the leaf blade). These morphological traits are important in estimating the leaf area, which directly affects photosynthetic efficiency, transpiration rates, and overall biomass accumulation. Larger leaf dimensions suggest more efficient canopy development and greater potential for light capture, both of which are essential for yield formation. Differences in leaf size between treatments provided insights into the influence of inoculation.

### *Total Plant Length*

Plant length was recorded as the cumulative extension of the stem and main root system after careful uprooting at the designated assessment period. This parameter offered a comprehensive measure of the combined development of the aerial and subterranean structures. Since *B. japonicum* inoculation primarily enhances root nodulation and nitrogen assimilation, measuring plant length allowed for the evaluation of treatment effects not only on shoot elongation but also on root development. A greater plant length indicated a balanced growth pattern, with potential implications for improved anchorage, nutrient uptake, and overall plant stability.

### *Physicochemical Analysis of Experimental Soil Samples*

Physicochemical properties of soil samples were analyzed before and after planting according to methods of Ghare and Kumbhar (2021).

### *Determination of Soil Nitrogen*

Soil nitrogen content was analyzed using the Kjeldahl method. A 10-gram sample of finely ground soil was digested with concentrated sulfuric acid ($H_2SO_4$), along with a catalyst mixture containing copper sulfate and selenium.

The resulting digest was then distilled with sodium hydroxide (NaOH) to liberate ammonia, which was captured in a boric acid solution and subsequently titrated with standardized hydrochloric acid (HCl).

Formula:

$$\%N = \frac{(\mathrm{V_s} - \mathrm{V_b}) \times N \times 14.007 \times 100}{1000 \times W}$$

Where:

$\mathrm{V_s}$ = volume of HCl used for sample titration (mL)

$\mathrm{V_b}$ = volume of HCl used for blank (mL)

N = normality of HCl

W = weight of soil sample (mg)

14.007 = atomic mass of nitrogen

### *Determination of Soil Electrical Conductivity*

Electrical conductivity was assessed with a conductivity meter. A suspension was created by combining soil and distilled water in a 1:2.5 (weight/volume) ratio, thoroughly shaken, and left to stabilize. The electrical conductivity of the resulting supernatant was then recorded in deciSiemens per meter (dS $m^{-1}$).

Formula:

$$EC = \frac{C \times K}{1000}$$

Where:

EC = electrical conductivity of the soil (dS $m^{-1}$)

C = observed conductivity reading (µS $cm^{-1}$)

K = cell constant of the electrode

### *Determination of Soil pH*

Soil pH was measured potentiometrically using a calibrated digital pH meter. A soil-to-water suspension was prepared at a 1:2.5 (weight/volume) ratio, thoroughly mixed, and left to stand for 30 minutes. The pH electrode was then inserted into the supernatant, and the pH value was directly recorded.

Formula:

$\mathrm{pH} = -\log_{10}[\mathrm{H+}]$

Where:

$[H^+]$ = hydrogen ion concentration in soil solution

### Determination of Soil Nitrate ($NO_3^-$)

Nitrate levels were measured using the Brucine colorimetric method. A 5-gram soil sample was extracted with 25 mL of 2M potassium chloride (KCl). The resulting extract was filtered, and a portion of it was reacted with a brucine-sulfanilic acid reagent. Absorbance was then recorded at 410 nm using a spectrophotometer.

Formula:

Where:

$$NO^{3-}(mg/kg) = \frac{A_s}{A_{std}} \times C_{std}\ (mg/L)\ \times \frac{V}{W}$$

$A_s$= absorbance of sample

$A_{std}$ = absorbance of standard

$C_{std}$ = concentration of nitrate standard (mg/L)

V = volume of extract (mL)

W = weight of soil (g)

### Determination of Available Phosphorus

Available phosphorus was measured using the Olsen method. A 5-gram soil sample was extracted with 25 mL of 0.5 M sodium bicarbonate ($NaHCO_3$) solution at pH 8.5. The extract was then filtered, and phosphorus content was determined colorimetrically by the molybdenum blue method, with absorbance measured at 882 nm.

Formula:

$$P\ (mg/kg) = \frac{A_s}{A_{std}} \times C_{std} \times \frac{V}{W}$$

Where:

$A_s$ = absorbance of sample

$A_{std}$ = absorbance of standard

$C_{std}$ = concentration of standard phosphorus solution (mg/L)

V = extract volume (mL)

W = soil weight (g)

### *Determination of Exchangeable Potassium*

Exchangeable potassium was determined using a flame photometer. A 5-gram soil sample was extracted with 1 M ammonium acetate solution at pH 7.0. The extract was then filtered and analyzed for potassium content using flame photometry.

Formula:

$$K\ (cmol/kg) = \frac{R_s}{R_{std}} \times C_{std} \times \frac{V}{W}$$

Where:

$R_s$ = flame photometer reading of sample

$R_{std}$ = reading of standard

$C_{std}$ = concentration of potassium standard (mg/L)

V = extract volume (mL)

W = soil weight (g)

### *Determination of Heavy Metals (Fe, Mg, Cu)*

Heavy metals (iron, magnesium, and copper) were determined using Atomic Absorption Spectrophotometry (AAS). One gram (1 g) of soil was digested with a mixture of nitric acid ($HNO_3$) and perchloric acid ($HClO_4$) in the ratio 4:1 until clear solution was obtained. The digested sample was diluted and analyzed using AAS at appropriate wavelengths for each element.

Formula:

$$C_m\ (mg/kg) = \frac{A_s}{A_{std}} \times C_{std} \times \frac{V}{W}$$

Where:

$C_m$ = concentration of metal in soil (mg/kg)

$A_s$ = absorbance of sample

$A_{std}$ = absorbance of standard

$C_{std}$ = concentration of standard solution (mg/L)

V = final digest volume (mL)

W = weight of soil sample (g)

### *Determination of moisture content*

Moisture content was assessed through oven-drying. Pre-weighed crucibles were used to hold 5 grams of the sample. The samples were dried in an oven at 105 ± 2 °C for 24 hours until a constant weight was reached. After cooling in a desiccator, the crucibles were weighed again, and moisture content was calculated based on the percentage of weight lost during drying.

Formula:

$$\text{Moisture\%} = \frac{(W1 - W2)}{W1} \times 100$$

Where: W1 = weight of sample before drying; W2 = weight of sample after drying

2.2.5.9 Determination of ash content

Ash was determined by complete combustion in a muffle furnace. Dried samples of 5 g were placed in pre-weighed crucibles and heated to 550 ± 25 °C for 4 hours until a light grey ash remained. Crucibles were cooled in a desiccator and reweighed. Ash content was calculated as the percentage residue remaining after ignition.

Formula:

$$\text{Ash\%} = \frac{(W1 - W2)}{Ws} \times 100$$

Where: W1 = weight of empty crucible; W2 = weight of crucible + ash; Ws = weight of sample.

### *Determination of Crude Fat*

Crude fat was determined using Soxhlet extraction with petroleum ether. Between 2 g of ground sample was placed in pre-weighed thimbles and extracted for 8 hours. After extraction, the solvent was removed and the thimbles were dried to constant weight. The percentage of ether extract was calculated based on weight loss of the sample.

Formula:

$$\text{Crude Fat\%} = \frac{(W1 - W2)}{Ws} \times 100$$

Where: W1 = weight of thimble + sample before extraction; W2 = weight of thimble + fat extract; Ws = weight of sample.

### *Determination of crude protein*

Total nitrogen was determined by the Kjeldahl method.1.0 g of sample was digested with concentrated sulfuric acid in the presence of a catalyst mixture until the digest was clear. The digest was diluted, made alkaline with NaOH, and distilled, with the liberated ammonia absorbed in boric acid solution. The trapped ammonia was titrated with standardized acid. Crude protein content was calculated by multiplying the total nitrogen value by the conversion factor of 6.25.

Formula:

$$\text{Nitrogen \%} = \frac{(\text{T} \times \text{N} \times 14.007)}{\text{Ws}} \times 100$$

$$\text{Crude Protein \%} = \text{Nitrogen \%} \times 6.25$$

Where: T = volume of titrant (mL); N = normality of acid; Ws = weight of sample.

### *Determination of Crude Fibre*

Crude fibre was determined by sequential acid and alkali digestion. Defatted samples were refluxed with 1.25% sulfuric acid for 30 minutes, filtered, washed and then refluxed with 1.25% sodium hydroxide for 30 minutes. The residue was filtered, washed, dried to constant weight, and weighed. The dried residue was then ashed at 550 °C, cooled and reweighed. Crude fibre was calculated as the percentage weight of the residue after correction for ash.

Formula:

$$\text{Crude Fibre \%} = \frac{(\text{W2} - \text{W3})}{\text{Ws}} \times 100$$

Where: W2 = weight of residue after drying; W3 = weight of ash; Ws = weight of sample

### *Determination of nitrogen-free extract*

Nitrogen-free extract (NFE) was calculated by difference. The percentage of NFE was obtained by subtracting the sum of moisture, ash, crude protein, crude fat, and crude fibre from 100. Formula:

NFE % = 100 – (% Moisture + % Ash + % Crude Protein + % Crude Fat + % Crude Fibre)

### *Determination of volatile matter and fixed carbon (peat and charcoal)*

Volatile matter in peat and charcoal was determined by heating dried samples in covered crucibles at 950 ± 25 °C for 7 minutes. The crucibles were cooled in a desiccator and weighed, and volatile matter was calculated as the percentage weight loss corrected for moisture and ash. Fixed carbon was obtained by difference.

Formula:

$$\text{Volatile Matter \%} = \frac{(W1 - W2)}{Ws} \times 100$$

$$\text{Fixed Carbon \%} = 100 - (\text{Moisture \%} + \text{Ash \%} + \text{Volatile Matter \%})$$

2.2.6 Statistical Analysis

Each treatment was replicated twice and the results were expressed as mean ± standard deviation. Statistical analysis was performed using SPSS (version 20.0) at a significant level of $p<0.05$.

## 2. RESULTS

### 2.1 Biochemical and Physiological Characterization of *Bradyrhizobium japonicum* USDA110

Table 1 revealed the biochemical characteristics of the isolate. The bacterium was identified to be a Gram-negative, rod-shaped, motile organism that tested positive to citrate utilization, catalase activity, and glucose fermentation, but negative for sucrose and lactose fermentation. Its Gram-negative rod morphology is in accordance with the usual description of Rhizobia as the family of *Bradyrhizobiaceae*. Citrate-utilization capability shows that the bacterium is metabolically adaptable, enabling it to survive in nutrient-variable soils; catalase positivity indicates survival in oxidative stress, which would be crucial when root nodules colonize a host plant because reactive oxygen species are frequently generated there. Carbohydrate profiling showed it to be able to use glucose and not sucrose or lactose, implying it is ecologically adaptable to depend on root exudates and soils simple sugars. In addition, its motility implies flagella movement, which plays a vital role in directed migration to soybean root hairs, an important step in symbiotic infection and nodule recruitment.

**Table 1:** Biochemical and Physiological Characteristics of *Bradyrhizobium japonicum* USDA110

| Probable Organism | Gram reaction | Shape | Citrate | Catalase | Sucrose | Glucose | Lactose | Motility |
|---|---|---|---|---|---|---|---|---|
| *Bradyrhizobium japonicum* | -ve | Rod | +ve | +ve | -ve | +ve | -ve | +ve |

Key: -ve – Negative, +ve – Positive

### *Growth Performance of Soybean under Charcoal and Peat Substrates*

Growth performance of soybean species 3f and 6f treated with charcoal and peat carriers of *B. japonicum* is presented in Tables 2 - 8 (Day 14-56). The measured parameters were plant height, the number of the leaves, width of the leaf, length of a leaf, and width of a plant.

### *Plant Height*

There was progressive growth in the height of plants throughout the growth period in all the treatment. There were always higher heights that were recorded in inoculated plants as compared to uninoculated controls. The greatest values were recorded in Charcoal 3f (110.00 cm) and Peat 6f (98.00 cm), and the lowest height was seen in the control of Charcoal 6f (35.00 cm). These findings indicate the beneficial role of *B. japonicum* inoculation on vegetative growth. More consistent increases were in the case of peat, but charcoal exhibited greater variability, although preferring higher increase in species 3f.

### *Number of Leaves*

This pattern was also repeated in the case of leaf production which got higher with age. The highest number of the leaves was counted in Peat 6f (45 leaves), and then in Charcoal 3f (31 leaves), by Day 56. Charcoal controls showed the lowest number of leaves, validating that inoculation stimulated leaf increases.

The more leaves, the more photosynthetic capacity, which means that the fixation of nitrogen promoted by *B. japonicum* was put at the heart of the canopy formation.

### *Leaf Morphology (Width and Length)*

Plant age enhanced the width and length of the leaves irrespective of treatment. Peat 6f generated the widest leaves at day 56 (6.50 cm), whereas the longest leaves were grown by Charcoal 3f (10.25 cm). Uninoculated controls produced smaller leaf sizes, however. These findings suggest that inoculated plants had a bigger photosynthetic surface which holds in accumulating more biomass and the general well-being of the plant.

### *Plant Width (Canopy Spread)*

By day 56, canopy spread including plant width was greatest in Charcoal 3f (37.75 cm) and Peat 6f (28.00 cm). Inoculated treatments were always superior to controls and the thinnest canopies measured in charcoal-grown uninoculated plants. This pattern also endorses the part of Bradyrhizobium in augmenting vegetative vitality and canopy development that is highly essential in maximizing light interception and yield.

**Table 2:** Performance of Cultivated Soybean Seeds Treated with Charcoal and Peat Transferors of *Bradyrhizobium japonicum* USDA110 at Day 21

| Plants | Plant height | No of leaf | Leaf width | Leaf length | Plant width |
|---|---|---|---|---|---|
| Charcoal 3f | $32.60 \pm 11.88^{a}$ | $8.50 \pm 3.54^{d}$ | $3.00 \pm 0.71^{g}$ | $4.40 \pm 0.57^{d}$ | $12.20 \pm 5.37^{e}$ |
| Peat 3f | $29.50 \pm 2.12^{b}$ | $9.00 \pm 1.41^{c}$ | $3.20 \pm 0.28^{f}$ | $4.50 \pm 0.71^{c}$ | $12.30 \pm 0.42^{d}$ |
| Charcoal 6f | $22.50 \pm 3.54^{d}$ | $10.50 \pm 0.71^{b}$ | $3.55 \pm 0.64^{c}$ | $5.25 \pm 0.35^{b}$ | $12.50 \pm 3.54^{c}$ |
| Peat 6f | $29.50 \pm 2.12^{b}$ | $11.50 \pm 0.71^{a}$ | $3.80 \pm 0.28^{b}$ | $4.10 \pm 0.14^{f}$ | $15.65 \pm 0.50^{b}$ |
| CT (Peat 6f) | $24.10 \pm 0.85^{c}$ | $10.50 \pm 0.71^{b}$ | $3.40 \pm 0.42^{e}$ | $4.25 \pm 0.35^{e}$ | $16.00 \pm 1.41^{a}$ |
| CT (Charcoal 6f) | $16.00 \pm 1.41^{g}$ | $6.00 \pm 1.41^{f}$ | $3.50 \pm 0.71^{d}$ | $4.05 \pm 0.35^{g}$ | $10.50 \pm 0.71^{g}$ |
| CT (Charcoal 3f) | $21.00 \pm 1.41^{e}$ | $6.50 \pm 0.71^{e}$ | $2.80 \pm 0.28^{h}$ | $4.05 \pm 0.07^{g}$ | $7.55 \pm 0.35^{h}$ |

| | | | | | |
|---|---|---|---|---|---|
| CT (Peat 3f) | 18.00 ± 0.00$^{f}$ | 9.00 ± 1.41$^{c}$ | 4.50 ± 0.71$^{a}$ | 5.35 ± 0.50$^{a}$ | 11.90 ± 0.71$^{f}$ |

Values are expressed as mean ± standard deviation. The values carrying the same superscript are not statistically significant from each other.

Key: CT = Control, 3F = TGx 1951-3F, 6F = TGx 1904-6F

**Table 3:** Performance of Cultivated Soybean Seeds Treated with Charcoal and Peat Transferors of *Bradyrhizobium japonicum* USDA110 at Day 28

| Plants | Plant height | No of leaf | Leaf width | Leaf length | Plant width |
|---|---|---|---|---|---|
| Charcoal 3f | 49.50±24.75$^{b}$ | 14.00 ± 2.83$^{b}$ | 3.80 ± 0.85$^{c}$ | 6.60 ± 1.98$^{a}$ | 13.50 ± 4.95$^{d}$ |
| Peat 3f | 44.60 ± 6.51$^{c}$ | 11.50 ± 2.12$^{e}$ | 3.40 ± 0.00$^{d}$ | 4.30 ± 0.42$^{f}$ | 13.00 ± 0.28$^{e}$ |
| Charcoal 6f | 24.00 ± 4.24$^{f}$ | 19.50 ± 6.36$^{a}$ | 3.70 ± 0.57$^{c}$ | 4.85 ± 0.92$^{e}$ | 15.50 ± 2.12$^{c}$ |
| Peat 6f | 51.25 ± 7.42$^{a}$ | 13.00 ± 1.41$^{c}$ | 4.20 ± 0.28$^{b}$ | 6.25 ± 0.35$^{b}$ | 20.75 ± 1.06$^{a}$ |
| CT (Peat 6f) | 30.75 ± 0.35$^{d}$ | 11.90 ± 0.14$^{d}$ | 4.25 ± 0.21$^{a}$ | 6.15 ± 0.21$^{c}$ | 16.90 ± 0.14$^{b}$ |
| CT (Charcoal 6f) | 19.95 ± 0.07$^{h}$ | 10.20 ± 0.28$^{f}$ | 3.15 ± 0.21$^{e}$ | 4.15 ± 0.21$^{h}$ | 10.40 ± 0.57$^{g}$ |
| CT (Charcoal 3f) | 27.85 ± 0.07$^{e}$ | 9.00 ± 0.00$^{h}$ | 3.00 ± 0.00$^{f}$ | 4.25 ± 0.35$^{g}$ | 12.75 ± 0.21$^{f}$ |
| CT (Peat 3f) | 20.20 ± 0.28$^{g}$ | 10.00 ± 1.41$^{g}$ | 4.20 ± 0.28$^{b}$ | 5.15 ± 0.21$^{d}$ | 8.85 ± 0.21$^{h}$ |

Values are expressed as mean ± standard deviation. The values carrying the same superscript are not statistically significant from each other.

Key: CT = Control, 3F = TGx 1951-3F, 6F = TGx 1904-6F

**Table 4:** Performance of Cultivated Soybean Seeds Treated with Charcoal and Peat Transferors of *Bradyrhizobium japonicum* USDA110 at Day 35

| Plants | Plant height | No of leaf | Leaf width | Leaf length | Plant width |
|---|---|---|---|---|---|
| Charcoal 3f | 72.50±24.75$^{b}$ | 19.50 ± 6.36$^{d}$ | 4.25 ± 1.06$^{c}$ | 6.80 ± 1.98$^{c}$ | 17.00 ± 2.83$^{d}$ |
| Peat 3f | 59.00±12.73$^{c}$ | 14.50 ± 6.36$^{e}$ | 3.50 ± 0.71$^{h}$ | 5.25 ± 0.35$^{f}$ | 17.50 ± 3.54$^{c}$ |

| | | | | | |
|---|---|---|---|---|---|
| Charcoal 6f | 25.00 ± 4.24$^{g}$ | 26.00 ± 8.49$^{a}$ | 3.80 ± 0.28$^{g}$ | 5.50 ± 0.71$^{e}$ | 14.50 ± 6.36$^{f}$ |
| Peat 6f | 74.50 ± 6.36$^{a}$ | 25.50 ± 2.12$^{b}$ | 4.65 ± 0.21$^{b}$ | 6.85 ± 1.20$^{b}$ | 21.00 ± 4.24$^{a}$ |
| CT (Peat 6f) | 34.60 ± 0.14$^{e}$ | 19.75 ± 0.35$^{c}$ | 4.15 ± 0.07$^{d}$ | 7.70 ± 0.28$^{a}$ | 19.85 ± 0.21$^{b}$ |
| CT (Charcoal 6f) | 21.75 ± 0.35$^{h}$ | 11.00 ± 0.00$^{g}$ | 4.10 ± 0.00$^{e}$ | 4.20 ± 0.14$^{h}$ | 10.30 ± 0.14$^{h}$ |
| CT (Charcoal 3f) | 41.20 ± 0.28$^{d}$ | 11.20 ± 0.28$^{f}$ | 3.90 ± 0.14$^{f}$ | 5.95 ± 0.07$^{d}$ | 13.20 ± 0.28$^{g}$ |
| CT (Peat 3f) | 29.80 ± 0.28$^{f}$ | 10.15 ± 0.21$^{h}$ | 4.70 ± 0.28$^{a}$ | 5.10 ± 0.14$^{g}$ | 14.95 ± 0.07$^{e}$ |

Values are expressed as mean ± standard deviation. The values carrying the same superscript are not statistically significant from each other.

Key: CT = Control, 3F = TGx 1951-3F, 6F = TGx 1904-6F

**Table 5:** Performance of Cultivated Soybean Seeds Treated with Charcoal and Peat Transferors of *Bradyrhizobium japonicum* USDA110 at Day 42

| Plants | Plant height | No of leaf | Leaf width | Leaf length | Plant width |
|---|---|---|---|---|---|
| Charcoal 3f | 88.00±16.97$^{b}$ | 21.50 ± 6.36$^{e}$ | 4.90 ± 0.57$^{b}$ | 8.00 ± 1.41$^{a}$ | 21.00 ± 5.66$^{c}$ |
| Peat 3f | 69.50 ± 6.36$^{c}$ | 23.50 ± 4.95$^{d}$ | 4.20 ± 0.14$^{e}$ | 6.30 ± 1.70$^{e}$ | 20.00 ± 7.07$^{d}$ |
| Charcoal 6f | 28.60 ± 1.27$^{g}$ | 35.50±20.51$^{a}$ | 4.00 ± 0.28$^{g}$ | 5.75 ± 0.92$^{f}$ | 16.00 ± 7.07$^{e}$ |
| Peat 6f | 90.00 ± 7.07$^{a}$ | 31.00 ± 1.41$^{b}$ | 5.25 ± 0.35$^{a}$ | 7.95 ± 2.47$^{b}$ | 26.60± 10.75$^{a}$ |
| CT (Peat 6f) | 43.45 ± 1.48$^{e}$ | 29.00 ± 1.41$^{c}$ | 4.45 ± 0.21$^{c}$ | 7.70 ± 0.14$^{c}$ | 26.00 ± 1.41$^{b}$ |
| CT (Charcoal 6f) | 25.50 ± 0.71$^{h}$ | 16.00 ± 1.41$^{f}$ | 3.50 ± 0.71$^{h}$ | 5.15 ± 0.21$^{g}$ | 12.00 ± 1.41$^{h}$ |

| | | | | | |
|---|---|---|---|---|---|
| CT (Charcoal 3f) | 51.50 ± 2.12$^{d}$ | 12.50 ± 0.71$^{g}$ | 4.10 ± 0.14$^{f}$ | 8.00 ± 1.41$^{a}$ | 15.00 ± 1.41$^{f}$ |
| CT (Peat 3f) | 34.50 ± 0.71$^{f}$ | 11.00 ± 1.41$^{h}$ | 4.25 ± 0.35$^{d}$ | 6.70 ± 0.28$^{d}$ | 13.50 ± 2.12$^{g}$ |

Values are expressed as mean ± standard deviation. The values carrying the same superscript are not statistically significant from each other.

Key: CT = Control, 3F = TGx 1951-3F, 6F = TGx 1904-6F

**Table 6:** Performance of Cultivated Soybean Seeds Treated with Charcoal and Peat Transferors of *Bradyrhizobium japonicum* USDA110 at Day 49

| Plants | Plant height | No of leaf | Leaf width | Leaf length | Plant width |
|---|---|---|---|---|---|
| Charcoal 3f | 106.25±15.91$^{a}$ | 26.50 ± 4.95$^{e}$ | 5.35 ± 0.50$^{b}$ | 9.00 ± 1.41$^{b}$ | 30.50 ± 7.64$^{a}$ |
| Peat 3f | 73.45 ± 7.71$^{d}$ | 30.50 ± 7.71$^{d}$ | 4.75 ± 0.35$^{d}$ | 7.50 ± 2.12$^{e}$ | 23.15 ± 7.28$^{d}$ |
| Charcoal 6f | 35.00 ± 7.07$^{g}$ | 46.00±28.28$^{a}$ | 4.45 ± 0.07$^{e}$ | 7.25 ± 2.76$^{f}$ | 17.70 ± 8.91$^{e}$ |
| Peat 6f | 97.50± 10.61$^{b}$ | 37.50 ± 7.78$^{b}$ | 5.75 ± 0.35$^{a}$ | 8.75 ± 3.18$^{c}$ | 27.50± 10.61$^{c}$ |
| CT (Peat 6f) | 75.00 ± 1.41$^{c}$ | 34.50 ± 0.71$^{c}$ | 5.30 ± 0.14$^{c}$ | 9.20 ± 0.28$^{a}$ | 30.20 ± 0.28$^{b}$ |
| CT (Charcoal 6f) | 30.50 ± 0.71$^{h}$ | 17.65 ± 0.92$^{g}$ | 3.85 ± 0.21$^{h}$ | 7.20 ± 0.28$^{g}$ | 11.85 ± 0.21$^{h}$ |
| CT (Charcoal 3f) | 66.70 ± 0.28$^{e}$ | 20.85 ± 0.21$^{f}$ | 4.10 ± 0.28$^{f}$ | 7.75 ± 0.35$^{d}$ | 15.10 ± 0.42$^{f}$ |
| CT (Peat 3f) | 39.75 ± 0.35$^{f}$ | 11.15 ± 0.21$^{h}$ | 4.00 ± 0.28$^{g}$ | 7.00 ± 0.42$^{h}$ | 12.90 ± 0.14$^{g}$ |

Values are expressed as mean ± standard deviation. The values carrying the same superscript are not statistically significant from each other.

Key: CT = Control, 3F = TGx 1951-3F, 6F = TGx 1904-6F

**Table 7:** Performance of Cultivated Soybean Seeds Treated with Charcoal and Peat Transferors of *Bradyrhizobium japonicum* USDA110 at Day 56

| Soybean Species | Plant height | No of leaf | Leaf width | Leaf length | Plant width |
|---|---|---|---|---|---|
| Charcoal 3f | $110.00 \pm 14.14^{a}$ | $31.50 \pm 4.95^{e}$ | $6.25 \pm 0.35^{b}$ | $10.25 \pm 1.06^{b}$ | $37.75 \pm 3.89^{a}$ |
| Peat 3f | $75.00 \pm 7.07^{d}$ | $33.50 \pm 4.95^{d}$ | $5.15 \pm 0.50^{e}$ | $8.10 \pm 1.56^{f}$ | $24.00 \pm 7.07^{d}$ |
| Charcoal 6f | $45.00 \pm 7.07^{f}$ | $50.00 \pm 28.28^{a}$ | $4.55 \pm 0.07^{g}$ | $7.65 \pm 2.62^{g}$ | $18.50 \pm 9.19^{e}$ |
| Peat 6f | $98.00 \pm 10.61^{b}$ | $45.00 \pm 7.07^{b}$ | $6.50 \pm 0.71^{a}$ | $10.00 \pm 2.83^{c}$ | $28.00 \pm 10.61^{c}$ |
| CT (Peat 6f) | $75.50 \pm 0.71^{c}$ | $40.50 \pm 0.71^{c}$ | $6.20 \pm 0.28^{c}$ | $10.50 \pm 0.71^{a}$ | $30.90 \pm 0.57^{b}$ |
| CT (Charcoal 6f) | $35.00 \pm 0.00^{h}$ | $23.00 \pm 1.41^{f}$ | $5.20 \pm 0.28^{d}$ | $8.20 \pm 0.28^{e}$ | $14.95 \pm 0.07^{g}$ |
| CT (Charcoal 3f) | $67.20 \pm 0.28^{e}$ | $22.00 \pm 0.00^{g}$ | $5.20 \pm 0.14^{d}$ | $8.75 \pm 0.35^{d}$ | $17.10 \pm 0.42^{f}$ |
| CT (Peat 3f) | $41.00 \pm 0.00^{g}$ | $12.50 \pm 0.71^{h}$ | $5.10 \pm 0.14^{f}$ | $4.90 \pm 0.57^{h}$ | $14.85 \pm 0.21^{h}$ |

Values are expressed as mean ± standard deviation. The values carrying the same superscript are not statistically significant from each other.
Key: CT = Control, 3F = TGx 1951-3F, 6F = TGx 1904-6F

### 2.2 Comparison Between Substrates

The findings depicted that peat and charcoal produced varied effects on the growth of soybean. There was more balanced growth with Peat and width growth with Leaf production was best recorded with Peat 6f. This could be because the peat has a greater amount of organic matter and can hold a lot of moisture and this would prefer the survival and activity of Rhizobia. However, charcoal was more variable but promoted more plant height and canopy distribution in species 3f. It could have had a porous structure to promote vertical growth as this helped cause aeration and root penetration.

## 2.3 Comparison Between Soybean Species

There was a response difference between the two soybean species with respect to the growth substrate. Species 3f worked better in charcoal, registering increase in plant height and canopy spread, species 6f did better in peat where they produced more leaves and extended leaf surfaces. This indicates a genotype and substrate interaction type of interaction in which soybean varieties exhibit substrate-selective growth preferences when inoculated with *Bradyrhizobium japonicum*.

### *Effects of Bradyrhizobium japonicum USDA110 Inoculation*

Inoculated soybean plants performed highly in all the growth parameters measured by the plant height, number of leaves, and general canopy development compared to the uninoculated controls. The inoculation advantages continued to gain momentum after day 28 and the difference in performance expanded significantly on day 56 when the inoculated plants almost doubled the growth measures of the control plants as recorded in Figure 4.1. These findings point to the success of *Bradyrhizobium japonicum* inoculation to stimulate healthy vegetative growth that is strongly associated with the increase in the fixation capacity of nitrogen in the root nodules

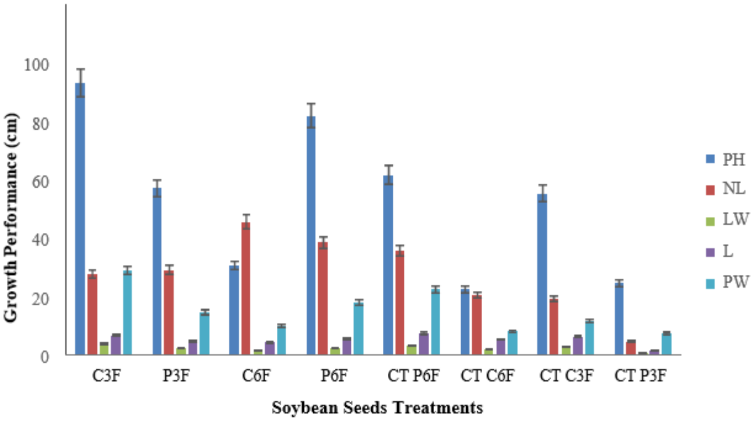


**Figure 1:** Performance index of Soybean in Charcoal and Peat Carriers of *Bradyrhizobium japonicum* USDA110 at day 56

**Key**

C3F = Soybean Seeds variety-TGx 1951-3f + Charcoal Carriers of *B. japonicum* USDA110

P3F = Soybean Seeds variety-TGx 1951-3f + Peat Carriers of *B. japonicum* USDA110

C6F = Soybean Seeds variety- TGx 1904- 6f + Charcoal Carriers of *B. japonicum* USDA110

P6F = Soybean Seeds variety- TGx 1904- 6f + Peat Carriers of *B. japonicum* USDA110

CT P6F = Control Peat TGx 1904- 6f, CT C6f = Control Charcoal TGx 1904- 6f, CT C3f = Control Charcoal TGx 1951- 3f, CT P3f = Control Peat TGx 1951- 3f, PH = plant height, NL = number of leaves, LW = leaf width, L = leaf length, PW = plant width

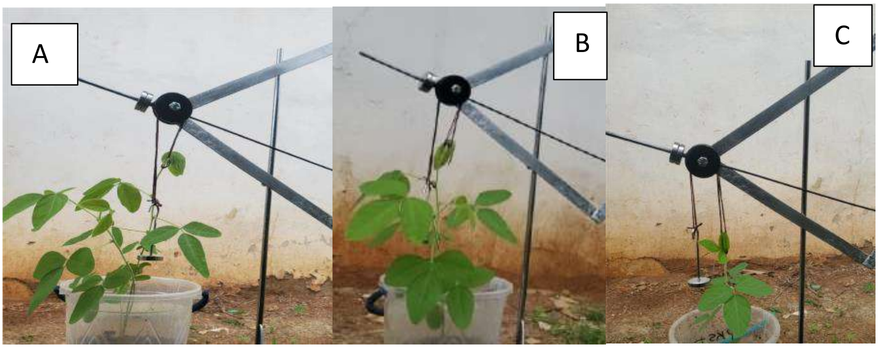


**Plate 1:** Cultivation of soybean seeds variety-TGx 1951-3f + Charcoal Carriers of *B. japonicum* USDA110A at Day 28 (A); + Peat Carriers of *B. japonicum* USDA110A at Day 28 (B); Control (C)

**Table 8:** Physicochemical Properties of Soil Samples Before and After Cultivation of Treated Soybean Seeds

| Parameters | Charcoal Before Planting | Charcoal After Planting | Peat Before Planting | Peat Before Planting |
|---|---|---|---|---|
| Total Nitrogen (%) | 0.34 | 0.38 | 0.50 | 0.49 |
| Electrical Conductivity | 0.12 | 0.13 | 0.16 | 0.15 |
| Nitrate | 15.6 | 17.6 | 21.7 | 22.9 |
| pH | 5.73 | 5.88 | 5.98 | 6.5 |
| Available phosphorus (mg/kg) | 3.58 | 3.69 | 3.85 | 3.97 |
| Potassium (cmol/kg) | 0.55 | 0.57 | 0.64 | 0.60 |
| Magnesium (cmol/kg) | 1.20 | 1.19 | 1.16 | 1.15 |
| Iron (mg/kg) | 423.7 | 422.7 | 418.8 | 419.2 |
| Copper (mg/kg) | 4.09 | 4.09 | 4.03 | 4.01 |

**Table 9:** Proximate profile of Biofertilizer Carriers

| Parameters | Charcoal | Peat |
|---|---|---|
| Moisture content (%) | 10.86 | 19.5 |
| Ash content (%) | 72.56 | 92.32 |
| Crude Protein (%) | 3.8 | 0.88 |
| Crude Fibre | 0.56 | 0.85 |
| Crude Fat (%) | 0.13 | 0.16 |
| Volatile Matter | 39.7 | 7.74 |
| Nitrogen-Free extract (%) | 65.7 | 96.11 |
| Fixed Carbon | 43.7 | 21.1 |

## 3. DISCUSSION

The study provided valuable insights into the growth response of soybean seeds varieties TGx 1951-3F and TGx 1904-6F when inoculated with *Bradyrhizobium japonicum* USDA110 using charcoal- and peat-based as carrier substrates.

The significant improvement in vegetative parameters such as plant height, leaf number, leaf area, and overall canopy development highlights the potential of this symbiotic bacterium to enhance soybean productivity under controlled and field conditions. The observed improvements in growth parameters also suggest that both carrier materials are effective in maintaining the viability and infectivity of the inoculant, although subtle variations in performance between charcoal and peat indicate that the choice of carrier could influence the efficiency of nodulation and nitrogen fixation.

The physiological and biochemical characteristics observed in this study testify to the identity of the isolate as *B. japonicum* and underscore its ecological competence as a nitrogen-fixing bacterium. The ability of the isolate to effectively utilize citrate, exhibit catalase activity, metabolize glucose, and tolerate oxidative stress conditions provides evidence of its robustness and adaptability to diverse soil environments. These characteristics are crucial for its survival in rhizosphere conditions, where competition with native soil microbes and exposure to environmental stresses could otherwise hinder nodulation efficiency. This finding is consistent with the work of Adeleke *et al.* (2021), who reported that *B. japonicum* possesses enhanced metabolic versatility, motility, and stress-resistance mechanisms that support its successful colonization of soybean roots and establishment of functional nodules.

The improved vegetative growth performance of soybeans in charcoal- and peat-based inoculants observed in this study corroborates earlier reports by Ashwin *et al.* (2023) and Beruk *et al.* (2024), who demonstrated that inoculation with Bradyrhizobium species significantly increased soybean height, leaf area, chlorophyll content, and canopy spread compared to uninoculated controls. These improvements are not merely morphological but directly linked to enhanced photosynthetic efficiency and better nutrient uptake, which ultimately translate into improved yield potential. The present findings, therefore, confirm that inoculation can serve as a cost-effective, environmentally friendly approach to boost soybean production, especially in nutrient deficient tropical soils.

Moreover, the results lend further support to the assertion that the physiological and biochemical traits of *B. japonicum* including citrate utilization, catalase activity, glucose metabolism, motility, and oxidative stress resistance, are key drivers of its ecological success and nitrogen fixing ability. These features collectively precondition the bacterium to establish a robust symbiotic relationship with soybean roots, enabling efficient nitrogen fixation and contributing to soil fertility improvement over time. This observation is of particular importance for smallholder farmers and sustainable agriculture systems, where over-reliance on synthetic nitrogen fertilizers is both economically burdensome and environmentally damaging.

Inoculation with charcoal-based and peat- *Bradyrhizobium japonicum* significantly improved key soil fertility parameters compared to the uninoculated control, underscoring the effectiveness of biological inoculants in improving soil health. Both treatments led to a marked increase in total nitrogen (TN) and nitrate content, confirming the stimulation of biological nitrogen fixation (BNF) and improved nitrogen cycling within the rhizosphere. This observation is in line with the findings of Volkogon *et al.* (2021) and Jiang *et al.* (2023), who reported that inoculation with effective *Rhizobium* strains enhances nitrogen fixation rates, leading to higher availability of plant-accessible nitrogen forms.

Furthermore, the peat-based inoculant produced the highest total nitrogen levels among treatments, suggesting that peat as a carrier material may provide a more favorable microenvironment for Rhizobia survival, nodulation efficiency, and long-term activity in the soil. This finding aligns with Gatabazi *et al.* (2024), who demonstrated that peat supports the proliferation of Rhizobia by maintaining adequate moisture, organic matter, and microbial habitat quality, which translate into better nodulation and nitrogen assimilation by soybean plants.

On the other hand, the charcoal-based inoculant significantly raised soil pH and available phosphorus (P), a result that is consistent with previous studies showing that biochar-based carriers help buffer soil acidity and release bound phosphorus into plant-available forms (Persaud *et al.,* 2023; Oyeyiola *et al.,* 2024).

This is particularly beneficial in acidic soils, where phosphorus availability is often a limiting factor due to fixation by iron and aluminum oxides. By improving pH, charcoal enhances microbial activity and nutrient solubility, which collectively improve the nutrient status of the rhizosphere.

Electrical conductivity (EC) and potassium (K) levels showed slight but measurable increases in both inoculated treatments, indicating enhanced nutrient cycling and cation exchange capacity within the soil matrix (Fang *et al.,* 2023). These changes suggest that *Rhizobia* activity, coupled with improved root growth and exudation, may have mobilized nutrients and facilitated their redistribution within the soil profile. Magnesium (Mg) levels remained relatively stable across treatments, implying that the inoculation did not significantly influence exchangeable Mg pools during the experimental period. Copper (Cu), however, showed a marginal decrease, which could be attributed to its uptake by the growing soybean plants or immobilization in soil organic complexes following improved microbial activity.

The findings of this study strengthen the argument for the wider adoption of B. japonicum-based biofertilizers, delivered through either charcoal or peat carriers, as part of an integrated soil fertility management strategy. By enhancing soybean vegetative growth, improving nitrogen availability, and reducing dependence on chemical inputs, B. japonicum inoculants have the potential to significantly boost soybean yields, improve soil health, and contribute to climate smart agricultural practices in the tropics.

In conclusion, these findings highlight that both peat and charcoal are effective carriers for B.japonicum, with each providing unique benefits. Peat appears to favor enhanced nitrogen enrichment and nodulation efficiency, while charcoal provides added advantages in improving soil pH, phosphorus availability, and overall nutrient bioavailability. The choice of carrier, therefore, can be strategically tailored depending on the specific soil constraints present in a given production system. In acidic soils, charcoal-based carriers may offer a dual benefit of inoculation and liming effect, while in nitrogen-deficient soils, peat may maximize nitrogen fixation potential. This complementary effect positions both carriers as viable components of integrated soil fertility management strategies, particularly in resource-limited tropical farming systems.

## 4. CONCLUSION

The study revealed relevance of charcoal as transfer of *B. japonicum* in soybean agronomy. The findings reinforced established role of *B. japonicum* in facilitating symbiotic nitrogen fixation, a process that is particularly critical in nitrogen-deficient tropical soils where soybean is cultivated. The outcomes also revealed that carrier type influenced soybean development in a variety-dependent manner. In soybean seed variety TGx 1904-6F, peat-based inoculation produced the tallest plants, confirming peat's long recognized suitability as a carrier due to its water-holding capacity, stability, and compatibility with Rhizobia. However, charcoal promoted superior canopy width and leaf number, suggesting that its porous and aerated matrix, creates a favourable environment for microbial survival and root colonization. Conversely, soybean seed variety TGx 1951-3F exhibited a stronger response to both charcoal and peat driving significant improvements in height, canopy expansion, and leaf production.

This study also revealed the potential of charcoal as competitive alternative to renowned peat as carriers of rhizobacteria in soybean agronomy. Also, charcoal is indigenous, biological and cheap against popularly imported peat. The benefits involved include accessibility to local and poor farmers and continuous accessibility. This will in turn generate high yield of soybean production; mostly needed in developing countries.

In conclusion, this research establishes that effective inoculation with *B. japonicum* remains the foundation of soybean productivity, but also demonstrates that the performance of inoculants can be significantly enhanced by careful consideration of carrier type and varietal specificity. These findings contribute to the growing body of knowledge on microbial biofertilizers, provide practical guidance for improving soybean cultivation.

*ACKNOWLEDGEMENT*

*Authors acknowledge the Tertiary Education Trust Fund (TETFund), Federal Republic of Nigeria for supporting this research through its Institutional Based Research grant of ETF/DR&D/CE/UNI/AKURE/IBR/2024.*

## REFERENCES

Abaidoo, R. C., Keyser, H. H., Singleton, P. W., Dashiell, K. E. and Sanginga, N. (2007). Population size, distribution, and symbiotic characteristics of indigenous tropical soybean nodulating *Rhizobia* in selected African soils. *Biology and Fertility of Soils*, 43, 749–761.

Adeleke, B. S., Ayangbenro, A. S. and Babalola, O.O. (2021). Genomic analysis of endophytic *Bacillus cereus* T4S and its plant growth-promoting traits. *Plants*, 10(9), 1776-1776.

Argal, M. S., Rawat, A. K., Aher, S. B. and Rajput, P. S. (2015). Bioefficacy and shelf life of *Rhizobium leguminosarum* loaded on different carriers. *Applied Biological Research*, 17(2), 125-131.

Ashwin, R., Bagyaraj, D. J. and Mohan Raju, B. (2023). Ameliorating the drought stress tolerance of a susceptible soybean cultivar, MAUS 2 through dual inoculation with selected *Rhizobia* and AM fungus. *Fungal Biology and Biotechnology*, 10(1): 10-11.

Beruk, H., Yoseph, T. and Ayalew, T. (2024). Unlocking the potential of inoculation with Bradyrhizobium for enhanced growth and symbiotic responses in soybean varieties under controlled conditions. *Agronomy*, 14(6): el280.

Bhuwan, H. and Ratnesh, K. (2021). Sensing methodologies in agriculture for monitoring biotic stress in plants due to pathogens and pests. *Inventions*, 6(2), 29-39.

Chao, W. L. and Alexander, M. (1984). Mineral soils as carriers for Rhizobium Inoculant. *Applied and Environmental Microbiology*, 47, 94–97.

Chiara, P., Alexandre, B., Andrea, T., Renaud, B. and Pierdomenico, P. (2019). Exploring legume *Rhizobia* symbiotic models for water logging tolerance. *Frontiers in Plant Science*, 10, 578-588.

Fang, X., Yang, Y., Zhao, Z., Zhou, Y., Liao, Y., Guan, Z. and Zhao, S. (2023). Optimum nitrogen, phosphorus and potassium fertilizer application increased chrysanthemum growth and quality by reinforcing the soil microbial community and nutrient cycling function. *Plants*, 12(23), 4062-4065.

Gatabazi, A., Ndhlala, A. R., Mvondo-She, M. A. and Mpai, S. (2024). Effectiveness of *Rhizobium tropici* sp. strain UD5 peat biofertilizer inoculants on growth, yield, and nitrogen concentration of common bean. *Nitrogen*, 5(1), 79-90.

Ghare, P. M. and Kumbhar, A. P. (2021). Study On Physicochemical Parameters of Soil Sample, *International Advanced Research Journal in Science, Engineering and Technology*, 8(9), 1-17.

Lucas, J. A., Probanza, A., Ramos, B., Barriuso, J. and Gutierrez M. (2004). Effects of inoculation with plant growth promoting rhizobacteria and *Sinorhizobium fredii* on biological nitrogen fixation, nodulation and growth of *Glycine max*. *Plant and Soil*, 267(1), 143-153.

Jiang, Y., Liu, J., Li, Y., Xiao, P., Liu, S., Shao, J. and Fan, L. (2023). Biochar amendment reduces biological nitrogen fixation and nitrogen use efficiency in cadmium contaminated paddy fields. *Journal of Environmental Management*, 344, 118338.

Kaneko, T., Nakamura, Y. and Sato, S. (2002). Complete genomic sequence of nitrogen fixing symbiotic bacterium *Bradyrhizobium japonicum* USDA110. *DNA Research*, 9, 189-197.

Olusola-Makinde, O. O. and Odamo, O. S. (2019). Comparative evaluation of *Bradyrhizobium japonicum* USDA110 transferors for greener and economic soybean (*Glycine max* L.) agronomy in Southwestern Nigeria. *Banat's Journal of Technology*, 15(2), 45-56.

Oyeyiola, Y. B., Ewetola, E. A., Kolawole, G. O. and Lawal, B. A. (2024). Comparative efficacy of biochar vs. cooking charcoal in urea-based soil fertility management: Impacts on soil quality, nutrient Retention, and maize performance. *Discover Soil*, 1(1), 17-27.

Paul, L. W., Nancy, K., Stanley, M. K., Mazvita, M. and Abdullahi, B. (2011). Putting nitrogen fixation to work for smallholder farmers in Africa. A revised manual for *Rhizobium* methods and standard protocols. *Plant and Soil*, 32, 256-258.

Persaud, T., Subramanian, G. and Lopez-Hernandez, D. (2023). Integrated Use of Bioinoculants and Biochar as a Strategy for Improving Crop Production of Marginal Soils in Guyana's Savannah: A Review. *World Environment*, 13(1), 29-42.

Roychowdhury, D., Paul, M. and Banerjee, S. K. (2015). Isolation identification and characterization of bacteria (*Rhizobium*) from chick pea (*Cicer* *arietinum*) and production of biofertilizer. *European Journal of Biotechnology and Bioscience*, 3(12), 26-29.

Volkogon, V. V., Dimova, S. B., Volkogon, K. I., Sidorenko, V. P. and Volkogon, M. V. (2021). Biological nitrogen fixation and denitrification in rhizosphere of potato plants in response to the fertilization and inoculation. *Frontiers in Sustainable Food Systems*, 5, 606379-606389.

Waclaw, J. (2022). Physiological response of soybean plants to seed coating and inoculation under pot experiment conditions. *Agronomy*, 12 (5), 1095-1099.

Yanni, Y.G., Rizk, R.Y., Corich, V. (2001). Natural endophytic association between *Rhizobium leguminosarum* bv. *trifolii* and rice roots and its potential to promote rice growth. Plant and Soil, 194, 99–114.

# CHAPTER 2

# MULTIDIMENSIONAL EFFECTS OF SUSTAINABLE LAND MANAGEMENT INDICATORS ON CASSAVA PRODUCTIVITY IN OYO STATE NIGERIA

[1]Oyewo Isaac. O. Jerry
[2]Oyewo E.O
[3]Adeoye A. Samson

---

[1] Department of Agribusiness Management Federal College of Forestry, Forestry Research Institute of Nigeria (FRIN), Ibadan, Nigeria, ojerry2@gmail.com ORCID ID: 0000-0003-0544-9918

[2] Department of Agribusiness Management Federal College of Forestry, Forestry Research Institute of Nigeria (FRIN), Ibadan, Nigeria

[3] Adeoye, A. Samson, Department of Agricultural Extension Management Federal College of Forestry Ibadan, Jericho Hills, P.M.B. 5087 Ibadan Oyo State, Nigeria, ORCID ID: 0000-0003-0909-5168

## INTRODUCTION

Land remains a fundamental factor of agricultural production and a critical resource for rural livelihoods in Nigeria. Beyond its economic importance, land performs a vital social security function, as rural households depend on it for food production, income generation, and subsistence, particularly during periods of economic hardship (Fabiyi, 1990). Recent global evidence further confirms that sustainable land use is central to achieving food security, climate resilience, and sustainable development goals in developing economies (FAO, 2021; IPBES, 2019). However, agricultural land in the tropics is increasingly threatened by declining soil fertility, land degradation, and unsustainable management practices, which pose serious challenges to agricultural productivity and environmental sustainability.

Most tropical soils are inherently fragile, characterized by low nutrient reserves, weak structural stability, and high susceptibility to erosion. In sub-Saharan Africa, land degradation driven by continuous cultivation, deforestation, and poor soil management has led to declining yields and increased vulnerability of smallholder farmers (Montanarella *et al*., 2018; Nkonya *et al*., 2020). In southwestern Nigeria, including Oyo State, intensified land use associated with population growth has resulted in shortened fallow periods, soil compaction, nutrient mining, and reduced water-holding capacity, thereby constraining crop productivity and long-term land sustainability.

Sustainable Land Management (SLM) has therefore emerged as a strategic approach for reconciling agricultural productivity with environmental conservation. SLM promotes the adoption of practices such as crop rotation, mulching, cover cropping, organic manure application, minimum tillage, and integrated soil fertility management, all of which have been shown to improve soil health and enhance farm productivity (FAO & ITPS, 2015; Lal, 2020; Pretty *et al*., 2018). Empirical studies across Africa indicate that adoption of SLM practices contributes significantly to improved yields, reduced land degradation, and enhanced ecosystem services (Kassie *et al*., 2018; Nyamekye *et al*., 2021).

Assessing sustainability, however, remains complex due to its multidimensional nature, encompassing biophysical, economic, and social dimensions.

Farm-level indicators are increasingly employed to evaluate sustainability because they serve as measurable proxies for production practices, environmental impacts, and resource-use efficiency (Dan *et al.*, 2001; Aimee & László, 2009). The Framework for Evaluation of Sustainable Land Management (FESLM) integrates critical dimensions such as productivity maintenance, risk reduction, environmental protection, economic viability, and social acceptability (Gameda *et al.*, 2002). Recent studies emphasize the need for composite indicator approaches that capture the interlinkages among these dimensions (OECD, 2020; Bachev *et al.*, 2022).

Fuzzy Set Theory (FST) provides a robust methodological framework for sustainability assessment by allowing partial membership and gradation between sustainable and unsustainable states. Unlike binary approaches, fuzzy logic captures the intensity of adoption of land management practices and supports the aggregation of diverse indicators measured on different scales (Cerioli & Zani, 1990; Dagum & Costa, 2004). Recent applications of fuzzy-based sustainability indices in agriculture demonstrate their effectiveness in capturing heterogeneity among farmers and guiding policy-relevant insights (Oyekale, 2018; Uddin *et al.*, 2020; Singh *et al.*, 2023).

Although several studies in Nigeria have examined soil conservation, land degradation, and adoption of sustainable agricultural practices (Rahji, 2005; Adeola, 2010; Raufu & Adetunji, 2012; Akinola *et al.*, 2015), recent literature highlights a gap in the quantitative aggregation of farm-level sustainability indicators and their direct linkage with productivity and technical efficiency, particularly using fuzzy-based approaches (Nkonya *et al.*, 2020; Nyamekye *et al.*, 2021). Moreover, limited attention has been given to individual farmers’ contributions to overall land sustainability within a unified analytical framework.

Cassava remains a key staple and cash crop in Nigeria and plays a vital role in food security and rural incomes. Recent studies emphasize that improving cassava productivity requires not only better input use but also sustainable land and soil management practices (FAO, 2021; Oyewo *et al.*, 2021).

Against this background, this study examines the multidimensional effects of sustainable land management indicators on land use and cassava productivity in Oyo State, Nigeria, using fuzzy logic analysis and a Cobb–Douglas production function. The study provides evidence on sustainability levels, indicator contributions, individual farmers' performance, and the rate of technical returns, contributing to informed policy design for sustainable agricultural development.

Marginal lands such as slopes and gravelly soils which under normal circumstances should be left under cover are now being exposed through farming activities. In the humid and sub-humid tropics, the traditional farming system, which is shifting cultivation, was adequate many years back as far as soil conservation is concerned. As a result of low population, small pieces of land were required for farming to obtain equilibrium of food production (Ishaq, 2008). Presently, the population is increasing and this necessitates sustainable land management practices in other to enhance crop yield

.

**Table 1:** Framework for Evaluation of Sustainable Land Management Indicators in Oyo State

| Maintenance of production (productivity) | Reduction of production risk (security) | Protects potentials of natural resources (protection) | Economically viable (viability) | Socially acceptable (acceptability) |
|---|---|---|---|---|
| Application of fertilizer | Drainage infiltration of water | Trends of vegetative covers | Land use intensity | Type of seeds |
| Addition of organic manure | Water holding capacity | Plant residue cover | Labour use intensity | Use of pesticides |
| Vigour of crop growth | Aggregation of soil | Wind or water erosion | Crop yield | Use of herbicides |
| | | Planting of cover crops | Profit per hectares | Use of chemical |

| | | | | |
|---|---|---|---|---|
| | Irrigation water level<br>Irrigation water quality<br>Salinity | Mulching of soil<br>Fallowing of land<br>Earthworm soil life<br>Tilth/ workability<br>Compaction and rooting<br>Crusting/emergency<br>Organic matter Contents | Labour productivity<br>Seed use intensity | poison in rivers<br>Industrial discharges |

Management issue cannot be taken for granted, given that these resources constitute the productive base for the Nigerian agriculture, upon which the livelihoods of many rural and urban household depend (Oyekale, 2012). The understanding of the quality use and management interaction of land as well as socio-economic factors and farmers' attitudes towards land management is also a key indicator of the sustainability of the resource. Moreover, poor incentives for natural resource conservation, together with among other socio-economic problems, have subjected the soils nutrients to serious exploitation and depletion. However, studies which had been conducted by various authors such as Rahji (2005), Adeola (2010), Raufu and Adetunji (2012), Ikechukwu *et al.,* (2013), Oladeebo *et al.,* (2013), Adedokun and Ogunyemi (2013), Amao *et al.,* (2013) Ademola and Olujide (2014) and Akinola *et al.,* (2015) on land management, soil conservation, adoption, degradation, awareness and sustainable agricultural practices had not examined the issue of farm level indicators indices, hence necessitating this study.

### *Objectives of the Study*

The broad objective of this study is to examine the multidimensional effects of sustainable land management indicators on land use and farmers' productivity in Oyo State, Nigeria.

The specific objectives are to:

1. construct a composite index of sustainable land use indicators among cassava farmers in the study area;
2. assess the relative contributions of individual sustainable land management indicators to land use sustainability;
3. examine individual farmers' contributions to sustainable land management using fuzzy logic analysis; and
4. analyze the rate of technical returns to inputs in cassava production using a Cobb–Douglas production function.

## 1. METHODOLOGY

### 1.1 The Study Area

This study was carried out in Oyo State, Nigeria. The State is located in the Southwestern part of the country. Oyo State consists of thirty three (33) Local Government Areas grouped under four (4) agricultural zones. The zones are: Ibadan-Ibarapa, Oyo, Saki and Ogbomoso Zones. Oyo State covers a total land area of about 27,249,000 square kilometers with a total population of about 5.6million (National Population Commission, 2006). It is situated between Latitude 7° N and 19°N and Longitude 2.5°E and 5°E of the meridian and it is bounded in the south by Ogun State, in the north by Kwara State, in the west it is partly bounded by Ogun State and partly by he Republic of Benin, while in the East by Osun State. (www.oyostate.gov.ng, http://oduainvestment.com.ng/portfolio-item/oyo-state/ 2014). Retrieved on February 16, 2023.

### 1.2 Sampling Frame

A two-stage sampling technique was employed in selecting 330 farmers from the four agricultural zones in Oyo State. Structured questionnaire was used to obtain primary data. The data collected were analysed with the use of Fuzzy logic analysis.

**Table 2:** Sampling Frame and Size

| Agricultural zones | LGA | Population of respondents | Sample selected | Sample size used | Total |
|---|---|---|---|---|---|
| Ibadan-Ibarapa | Ibarapa East | 80 | 48 | 45 | |
| | Egbeda | 58 | 35 | 35 | 80 |
| Oyo | Atiba | 90 | 54 | 50 | |
| | Itesiwaju | 66 | 40 | 40 | 90 |
| Saki | Atisbo | 60 | 36 | 35 | |
| | Iwajowa | 59 | 35 | 35 | 70 |
| Ogbomoso | Ogbomoso North | 98 | 58 | 50 | |
| | Ogo-oluwa | 69 | 41 | 40 | 90 |
| 4 | 8 | 580 | 348 | 330 | 330 |

**Source:** Author computation

## 1.3 Data Collection

The study used data mainly from primary source. The data (primary source) were obtained from the farmers' during the 2018 agricultural season with the use of structured questionnaire and interview schedule. These were administered and interpreted by the researcher and trained enumerators to the local language which the farmers understood.

## 1.4 Data Analysis

Fuzzy Sets Theory (FST) was used to compute the composite indicators of sustainable land management from selected farm level indicators, and individual farmers sustainable land use indices while descriptive statistics was used analyse the relative contributions of sustainable land use Indices (SLUI) among the farmers and Cobb-Douglass production model was used to analyse farmers Rate of Technical Returns (RTS) (table 3)

**Table 3:** Analysis of Objectives

| Objectives | Meaning | Data required | Sources of data | Method of data analysis |
|---|---|---|---|---|
| To construct index of sustainable land use indicators (IULU) | To study the farm level indicators that are responsible for land being sustainable | Factors such as, vigour of crop growth, erosion runoff, pesticides, crop yield. | Primary | Fuzzy Logic |
| Analyse the relative contributions of sustainable land use Indices (SLUI) among the farmers. | To describe the decomposed indicators of land sustainability and their implications. | Mulching of crop, cover crop, land fallowing, herbicides use, pesticides. | Primary | Descriptive statistics |
| Analyse the individual farmers' contributions of (SLMI) to sustainable land use. | To examine the individual farmers level of sustainable land use. | Factors such as, vigour of crop growth, erosion runoff, pesticides, crop yield. | Primary | Fuzzy Logic |
| Examine the rate of technical return in farmers' productivity in the study area. | To analyse the return to scale on cassava farmers productivity in the study | Farm size, credit used, fertilizer used, labour used | Primary | Production Model |

## 1.5 Model Specification

### *Fuzzy Logic Analysis*

Using fuzzy set theory, a set of composite farm level indicators was constructed in order to analyze different dimensions of sustainable land management using (FESLM) in Table 3.3.

Each indicator was calculated as one-dimensional sustainability ratio, thus allowing a comparison among indicators on the dimensions of sustainable land management. According to Oyekale (2012) farm level indicators of sustainable land use often take the form of simple 'yes/no' dichotomies. In this case Xij is 0 or 1. However, some indicators may involve more than two ordered categories (for example, discrete categorical variables and continuous categorical variables), reflecting different degree of deprivation. Consider the general case of c = 1 to C ordered categories of some deprivation indicator, with c = 1 representing the most deprived and c = C the least deprived situation. Let ci be the category to which individual *i* belongs. Cerioli and Zani (1990), assuming that the rank of the categories represents an equally-spaced metric variable, assigned to the individual a deprivation score as:

$$Xij = (C-ci) / (C-1) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where $1 < ci < C$, by summarizing the key notions about sustainable land management based on the theory of fuzzy sets and in particular on the work of Dagum and Costa (2004).

i. Sustainable land management in the given space ($a_i$)

Therefore, Xij needs not to be compulsorily 0 or 1, but $0 \leq Xij \leq 1$ when there are many categories of the jth indicator and the household possesses the attribute with intensity.

The sustainable land management index of a household, $U_\beta$ (ai), is defined as the weighted average of Xij,

$$U_\beta(ai) = \sum_{j=1}^{m} Xij\, wj / \sum_{j=1}^{m} wj \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The function of the i-th farmer (i = 1.........n) belonging to the fuzzy subset $_\beta$ in relation to the j-th attribute (j = 1......m) is defined as follows

$$X_{ij} = U_\beta\ (X_1(a_i)),\ 0 \leq 1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

In this case:

Xij = 1, if the i-th farmer does not have the j-th attribute;

Xij = 0, if the i-th farmer possesses the j-th attribute;

$0 < Xij < 1$, if the i-th farmer has the j-th attribute with an intensity between (0, 1).

$U_\beta$ (ai) = equation $U_\beta$ (ai) measures the ratio of the sustainable land management of the i-th farmer, where $w_i$ is the weight attached to the j-th attribute and where;

$0 \leq U_\beta (ai) \leq 1$

The behaviour of the function of belonging (to a fuzzy subset) is the following;

$U_\beta$ (ai) = 0, if ai possesses the m attributes;

$U_\beta$ (ai) = 1, if ai is totally deprived of the m attributes;

$0 < U_\beta (ai) < 1$. If ai is partially or totally deprived of some attributes, but not completely deprived of all attributes.

Weight wj represents the intensity of deprivation linked to attribute Xj. It is an inverse function of the degree of deprivation of this attribute for the farmer population. The smaller the number of households with attribute Xj is, the bigger the weight wj will be. Cerioli and Zani (1990) defined a weight that verifies this property, namely;

Wj = $\log[\sum_{j=1}^{n} g(a_i)/\sum_{j=1}^{n} x_n g(a_i)]$ ......................................... (4)

$\sum_{j=1}^{n} x_n g(a_i) > 0$

Where $g(a_i)$ refers to the frequency (weight) with which respondent $a_i$ of the population was observed;

$g(a_i)\sum_{j=1}^{n} x_n g(a_i)$ is the relative frequency with which sample $a_i$ of the population observed, g(ai) is equal to n times the relative frequency of farmers in the total population.

Therefore, $\sum_{j=1}^{n} x_n g(a_i)=n$, However, if nighters of the farmer posses an attribute, it has to be removed because it has no relevant to the sustainable land use.

In equation (5), the denominator of the logarithm is always positive. If the value Xij = 0, was part of the possible sets, that would mean that there would be no deprivation in Xj. The fuzzy index of sustainability of set A is a weighted mean of $\mu_B (a_i)$ given by equation (4)

In addition to determining the multidimensional sustainable land management for i-th farmer and that for the overall population, the use of the theory of fuzzy sets makes it possible to calculate a uni-dimensional index for each one of the j attributes considered.

$U_{\beta}\ (X_j) = \sum_{j=1}^{n} x_n g(a_i)/ \sum_{j=1}^{n} g(a_i)$ j = 1, 2, ...............m........................................ (5)

$U_{\beta}\ (X_j)$ defines the degree of deprivation of the jth attribute for the population of the respondent. The overall fuzzy index of sustainable land management can also be defined as a weighted average of uni-dimensional indices for each attribute;

$U_{\beta} = \sum_{j=1}^{n} x_n g(a_i)/ \sum_{j=1}^{n} g(a_i) = \sum_{i=1}^{m} \mu_{\beta}(X_i) W_i / \sum_{i=1}^{m} w_i = 1,$ 2,.........m...............(6)

**Elasticity Model: Measuring Rate of Technical Return**

Y=f(X1,X2…………………..X5)…………………………….. (1)

**Cobb-Douglas Production Function**

$LnYi=LnA+\beta i \sum_{I=1}^{5} Lni+ \mu$………………………………….. (2)

Y = Cassava yield (kg/ha)

$X_1$ = Farm size (hectares)

$X_2$ = Credit (naira)

$X_3$ = Labour (man day)

$X_4$ = Fertilizer (kg)

$X_5$ = Stem cuttings (bundles)

$LnY=(bo+b1lnX_1 + b2lnX2 + b3lnX_3 + b_{4lnX4} + b_{5lnX5} + \mu)$………… (3)

When Y = dependent Variable, X = independent Variables

$\mu$ = error term, $b_1$ = parametric estimates and $b_0$ = the intercept term

A and $B_i$ = parameters estimated (i = 1, 2... 5)

$X_i$ = the vector of transformations of the ith input used by jth farm

$\beta$ = a vector of unknown parameters and U = random variables

The Cobb-Douglas Production Function was used because it is required that the production function be self dual. Also this functional form has been used by various scholars such as Olagunju *et al.,* 2010; Olarinde 2011; Fawole and Rahji, 2016 and Akpan *et al*., 2017 on farm productivity for both developing and developed countries that the sets of inputs with positive elasticity were utilized in an efficient manner and such have kept production in various stages of elasticity.

The Cobb-Douglass Production Model was also explained by Diewert *et al*., (2011) that the production elasticity of farmers is positively signed and less than unity but not less than zero If $\gamma = 1$, then there are constant returns to scale a proportional change in all inputs results in an equal proportionate change in output, if $\gamma > 1$, there are increasing returns to scale and if $\gamma < 1$ (though not less than 0, given the possibility of free disposal), then there are decreasing returns to scale in farmers productivity. Output elasticity measures the responsiveness of output to a change in levels of physical inputs used in production ceteris paribus. Therefore, this processes need to be looked into in order to examine farmers' technical returns on cassava production in the study area.

## 2. RESULTS AND DISCUSSION

### *Contributive Effects of Land Indicators Aggregation to Farmers Land use*

From the result in Table 4 using the fuzzy logic model as specified in equation (1) to (6) of the fuzzy set theory, the contribution of SLM indicators to sustainable land us were identified.

Application of fuzzy set theory was due to its attempts to standardize all the variables that have different predictor, variables with different units of measurement and allows the decomposition of the sustainability land use indices based on the contributions of each indicator or attributes, it also determining the multidimensional sustainable land management for each farmer and that for the overall population, the use of this theory of fuzzy sets makes it possible to calculate a uni-dimensional index for each one of the attributes considered.

It was therefore revealed that land fallowing contributes absolute value of 0.009 and relatively 3.20% to sustainability because same pieces of farm land were used periodically for agricultural activities which may cause soil nutrients depletion and degradation (Oyekale, 2012). Compaction and rooting has absolute contribution of 0.009 with 3.20% relative contribution to sustainability because this may affects the sustaining power of the crop root to penetrate soil due to the hardness of the nature of the soil.

Residue cover has absolute contribution of 0.009 with relative contribution of 3.20% to sustainability, this shows that surface residue though present, were not properly covering the soil which could give room for wind or water erosion with absolute contribution of 0.009 and relatively contributes 3.20% to sustainability, to wash or blow away the top soil and affect the soil water holding capacity thereby exposing the top soil surface to depletion which may in turn have a negative effect on small scale cassava farmers' production and sustainability, plot level of fertilizer application had absolute contribution of 0.007 with 2.7% relative contribution, this shows that fertilizer was applied in the right quantity and up to specification, this is in line with Rahman, (2013). This could be due to the number of year of farming experience and majority of them who had one form of formal education which however, could enhance productivity, sustaining agricultural production and maintenance of soil nutrients lost.

Stem use intensity, profit per hectare, labour use intensity, vigour of crop growth, this enhance the maintenance of soil covers because the crops were found to be healthy and had uniform growth which could be due to the use of improved stem cuttings and increases crop stocking density and hereby increased farmers profit per hectare, land use intensity, proper use of chemical poison, proper management of industrial discharge from water been polluted and avoid environmental pollution which may be hazardous to animals even the farmers themselves and enhance increased labour productivity among others contribute absolutely 0.006, 0.006, 0.007, 0.007, 0.007 and 0.007 with relative contribution of 2.1%, 2.0%, 2.3%, 2.3%, 2.3% and 2.3% respectively to sustainable land management in the study. This implies that these indicators among others may influence sustainability and crop output positively; an increase, better management and adoption of these indicators could bring an increase in crop production, prevent soil erosion and land degradation, maintenance of production, reduction of production risk, protects potentials of natural resources as well as environmental pollution in the study area.

The result further revealed that the computed average of sustainable land indices (SLI) of 0.26 obtained indicated that farmers' land management practices in the study area are generally sustainable because the farther away the index value from 1 and the closer the index value is to 0 the better the sustainability. This is in line with Kayode *et al*., (2017), Oyewo *et al*., 2020 and conforms to the findings of Oyekale (2012). However, the SLI value which is 26% indicated that the aggregated indicator contributed 74 % to land conservation and sustainability in the study area.

**Table 4:** Contributive Effects of SL Indicators to Farmers Land Use

| **+ SLM Indicators** | ***Absolute contribution** | ****Relative contribution (%)** |
|---|---|---|
| Vigour of crop growth | 0.0064 | 2.317233483 |
| Trend of vegetative covers | 0.0087 | 3.172457796 |
| Residue cover | 0.0088 | 3.204165584 |
| Crop yield | 0.0082 | 2.980865299 |
| Labour productivity | 0.0072 | 2.626626269 |
| Profit per hectare | 0.0056 | 2.026445528 |
| Organic matter contents | 0.0078 | 2.840350661 |
| Drainage/infiltration of water | 0.0087 | 3.162153270 |
| Water holding capacity | 0.0088 | 3.189395739 |
| Aggregation of soil | 0.0087 | 3.154559936 |
| Earthworm/ soil life | 0.0083 | 3.024332006 |
| Compaction and rooting | 0.0088 | 3.202386116 |
| Crusting/emergency | 0.0088 | 3.184818606 |
| Tilth/ workability | 0.0086 | 3.118113701 |
| Wind or water erosion | 0.0087 | 3.150813599 |
| Salinity | 0.0088 | 3.209217214 |
| Plot level application fertilizer | 0.0074 | 2.695404096 |
| Addition of organic manure | 0.0075 | 2.706514029 |
| Mulching of crops | 0.0088 | 3.183196149 |
| Minimum tillage | 0.0088 | 3.189936159 |
| Cover crops | 0.0087 | 3.175581225 |
| Rotation of crops | 0.0088 | 3.207030646 |
| Land fallowing | 0.0088 | 3.190824110 |
| Irrigation Water level | 0.0082 | 2.981777222 |
| Irrigation Water quality | 0.0087 | 3.171362817 |
| Use of Pesticide | 0.0088 | 3.190824110 |

| | | |
|---|---|---|
| Use of Herbicide | 0.0076 | 2.758734516 |
| Use of chemical poison | 0.0067 | 2.447056059 |
| Industrial discharges | 0.0069 | 2.495042768 |
| Land use intensity | 0.0069 | 2.518237365 |
| Labour use intensity | 0.0065 | 2.358827751 |
| Type of stem cuttings | 0.0077 | 2.800804515 |
| Stem use intensity | 0.0059 | 2.125136962 |
| Total Computed (SLUI) | 0.2637 | 100 |

Author computation

Note: (*): Absolute contribution and (**): Relative contribution

(*): This is the raw index score of the fuzzified indicators analysed by fuzzy logic using MATLAB.

(**): This is the value of the fuzzified index score in percentage.

(+): Indicators of sustainable land management

### 2.1 Farmers' Contributive effects to Land Use Sustainability

From Table 5, the individual farmers contributions to land sustainability using fuzzy logic model in equation (1) to (6) and Table 1 using the framework for evaluating sustainable land management (FESLM) were analysed by the application of fuzzy set theory due to its attempts to standardize all the variables that have different predictor and different units of measurement and allows the decomposition of the sustainability land use indices based on the contributions of each indicator or attributes, it also determining the multidimensional sustainable land management for each farmer which ranges between 1 and 0, it was therefore revealed that farmers showed varied level of contributions sustainability ranging from the lowest 0.00004 to the highest 0.95650 with mean of 0.264 and frequency of occurrence of the decomposed predicted SLMI in decile range showed that 5.2% had less than 0.1, majority (60%) of the farmers had SLMI of between 0.1-0.2, 31.2% had SLMI of between 0.3-0.4, 3.0% had between 0.5-0.6 while 0.6% had between 0.9-1.0 sustainable land management index with Minimum index of 0.00004 and Maximum index of 0.95650 and overall mean index of the farmers was 0.264 (26.4%) indicating that the farmers are sustainable at 73.6% level.

However, according to fuzzy set theory used, the closer the decomposed value is to zero the better the individual farmers' contributions to sustainability in the study area. Majority (96.4%) of the farmers adopt sustainable land management practices with the proper combination and use of the farm level management indicators which enhanced farmers' productivity, soil conservation and reduce land degradation in the study area. This therefore shows that there is a wider distribution to sustainability among the farmers and there is a considerable room for effecting improvements in the SLM and conservation practices as reflected in Table 5

**Table 5:** Range and Distribution of Individual Farmer's Sustainable Land Use Indices

| + Sustainable land use Index | Frequency | Percentage |
|---|---|---|
| 0.0-0.1 | 17 | 5.2 |
| 0.1-0.2 | 198 | 60.0 |
| 0.3-0.4 | 103 | 31.2 |
| 0.5-0.6 | 10 | 3.0 |
| 0.7-0.8 | 0 | 0.0 |
| 0.9-1.0 | 2 | 0.6 |
| Total | 330 | 100 |
| Maximum SLUI | 0.95650 | |
| Minimum SLUI | 0.00004 | |
| Total Mean SLUI | 0.26372 | |

Source: Author computation 2016

Note: (+) Fuzzified values generated from the decomposed multidimensional sustainable land management indicators for each farmer which ranges between 0 and 1

## 2.2 Rate of Technical Returns on cassava Farmers' Production in the Study Area

Table 6 shows that the use of using the Cob-Douglass Production Model in linear form explains the production elasticity of the farmer. Farm size, credit, labour and fertilizer were positive and less than unity but not less than zero If $\ell = 1$, then there are constant returns to scale: any proportional change in all inputs results in an equal-proportionate change in output. If $\ell > 1$, there are increasing returns to scale and if $\ell < 1$ (though not less than 0, given the possibility of free disposal) and as also explained by Diewert *et al.*, (2011), then there are decreasing returns to scale therefore, showed that cassava production was productive in the study area considering the return to scale value of 0.904 which indicates a positive decreasing return to scale and shows that production was in stage II of the production surface which is the only economical and rational stage of production. This implies that for a unit increase in farm size, credit, labour and fertilizer there will be a positive and significant percentage increase in the cassava output, ( i.e. $\ell = 0.562$, a 1% increase in farm size usage would lead to approximately 56% increase in cassava output). This is in consonance with the work of Olarinde (2011) and Oyewo *et al.*, (2021) also supported by Fawole and Rahji (2016) that the sets of inputs with positive elasticity were utilized in efficient manner and such have kept production in rational stage of production and also conform to the findings of Akpan *et al.*, (2017). The Return to Scale (RTS) of 0.904 (Table 3) indicated that for every 100% increase in the combination of inputs used there was a corresponding 90.4% in the corresponding output of cassava production in the study. However, there is room for improvement with the present scope of production by the adoption of these combinations of the physical inputs (farm size, credit, labour, fertilizer and cassava stem cuttings) and better sustainable land management's practices which may enhance productivity among the farmers by 9.6% through the combination of the factors of production in the study area.

**Table 6:** Rate of Technical Return in Farmers' Productivity

| **Variables** | **Elasticity** |
|---|---|
| Farm size | 0.562 |
| Credit | 0.088 |
| Labour | 0.036 |
| Fertilizer | 0.028 |
| Stem cuttings | 0.190 |
| **RTS** | **0.904** |

**Source:** Author computation

## CONCLUSION

This study demonstrated that sustainable land management practices play a critical role in enhancing land use sustainability and cassava productivity in Oyo State, Nigeria. The application of fuzzy set theory revealed that most farmers adopt environmentally sustainable practices, with aggregated indicators contributing substantially to land conservation. The majority of farmers exhibited low sustainable land use index values, indicating favorable sustainability outcomes, while the overall index confirmed that land degradation risks remain relatively low in the study area. Furthermore, the production analysis established that cassava farmers operate within the economically rational stage of production, characterized by positive but diminishing returns to scale. Key inputs such as farm size, labour, credit, fertilizer, and improved cassava stems significantly influenced productivity. Despite these positive outcomes, the results also suggest that productivity and sustainability can be further enhanced through improved input efficiency and deeper adoption of conservation-oriented practices. Overall, sustainable land management remains a viable pathway for improving agricultural productivity while preserving soil resources in the study area.

"This study contributes directly to the achievement of the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) through the promotion of sustainable agricultural productivity, and SDG 15 (Life on Land) by addressing land degradation and sustainable land use. The findings also support SDGs 1, 12, and 13 by enhancing farmers' livelihoods, promoting responsible resource use, and strengthening climate resilience."

## RECOMMENDATIONS

### *Policy and Practical Recommendations*

Based on the findings, the study recommends that:

- Promotion of sustainable agronomic practices, such as crop rotation, mulching, land fallowing, cover cropping, and minimum tillage, should be intensified through extension services to further enhance soil conservation.
- Access to improved cassava stem varieties and appropriate fertilizer use should be strengthened through government and private-sector interventions to boost productivity while maintaining land sustainability.
- Farmer training programs should focus on improving awareness and technical capacity in sustainable land management, particularly in erosion control and organic matter management.
- Credit access and input support schemes should be expanded to enable farmers to optimize the use of productive inputs and improve technical efficiency.
- Policy frameworks on land resource management should integrate fuzzy-based sustainability indicators as monitoring tools to guide evidence-based agricultural planning and environmental conservation.

## REFERENCES

Adedokun, A. S. and Ogunyemi, O. I. (2013). Sustainable Agricultural Practices and Arable

Ademola, A.O and Olujide, M.G. (2014). Soil Conservation practices of Arable Crop

Adeola, R.G. (2010). Influence of Socio-Economic Factors on the Adoption of Soil

Aimee, R and László,P. (2009). Linking Farm-Level Measurement Systems to Environmental

Akpan, S.B., Adah, A. J and Udoh, E. J. (2017). Assessment of Farm Factor Productivity of

Amao, J.O., Ayantoye K. and Aluko, A.M. (2013). Land Degradation, Soil Conservation and

Bachev, H., Ivanov, B., & Toteva, D. (2022). Assessment of agricultural sustainability: New challenges and approaches. *Journal of Cleaner Production*, 338, 130553.

Cerioli A, and Zani, S. (1990). A Fuzzy Approach to the Measurement of Poverty. In: C

Conservation Measures in Ibadan/Ibarapa Agricultural Zone of Oyo State. *Report and Opinion*, *2*(7): 42-47.

Crop Farmers in South-Western Nigeria. *Global Journal of Science Frontier Research in Agriculture and Biology*. *12*(1):8-14.

Dagum, M, and Costa, C. (2004). "Analysis and Measurement of Poverty Univariate and

Dagum, M. (Eds.): *Income and Wealth Distribution, Inequality and Poverty*. Berlin: Springer Verlag, pp. 272- 284.

Dan, R., Phil, W., Trevor, Y and Michael B. (2001). Constructing a Farm Level Indicator of Sustainable Agricultural Practice, *Ecological Economics 39,* 463-478

FAO & ITPS. (2015). *Status of the world's soil resources* (SWSR). Rome: FAO

FAO. (2021). *The state of the world's land and water resources for food and agriculture*. Rome: FAO.

Farmers in Atisbo Local Government Area of Oyo State, Nigeria. *Advance in Research*, *2*(12): 879-888.

Farmers Productivity in Lagos State, Nigeria. *Journal of Sustainable Development in Africa*, *14*(5): 201-212

Fawole, W.O and Rahji, M.A.Y. (2016). Determinants of Productivity among Farmers in Ondo

Gameda, S., Dumanski, J and Acton, D. (2002) Farm Level Indicators of Sustainable Land

Ikechukwu, I. I and Nwankwo, O.C. (2013), Socio-economic determinants of farmland management practices in Umuahia North local government area, Abia State, Nigeria. *Journal of Agriculture and Social Research, 13*(1): 50-55.

Investment on Efficiency of Cassava Production in Oyo State of Nigeria. *Journal of Biology, Agriculture and Healthcare. 3*(13):47-52.

IPBES. (2019). *Global assessment report on biodiversity and ecosystem services*. Bonn: IPBES.

Is-haq, O.O (2008). Afforestation and Reforestation: The UNILORIN Experiment. Paper Presented at the High Level Technical Workshop on Afforestation and Climate Change in Africa December 15-17, 2008. Organised by the Centre for Human Security of the Olusegun Obasanjo Presidential Library (OOPL) and Nigeria Tree Planters. pp 33.

Kassie, M., Teklewold, H., Jaleta, M., Marenya, P., & Erenstein, O. (2018). Adoption of sustainable intensification practices. *Land Use Policy*, 72, 175–185.

Kayode, A.O., Oladipo, F.O. and Daudu, A.K. (2017). Determinants of Adoption of Land

Lal, R. (2020). Regenerative agriculture for food and climate. *Journal of Soil and Water Conservation*, 75(5), 123A–124A

Land Management Practices among Agroforestry Farmers in Oyo State, Nigeria. *Journal of Forestry Research and Management (JFRM),* 17(2), 68-74.

Management for the Development of Decision Support Systems pp 1-9.

Management Practices in Kogi State Nigeria: A Gender Analysis. *Agro-Science*, *16* (2): 52-58.

Montanarella, L., Scholes, R., & Brainich, A. (2018). The IPBES assessment on land degradation and restoration. *Land Degradation & Developmen*t, 29(6), 175–180

Multivariate Approaches and Their Policy Implications: A Case Study of Italy" In Dagum C. and Ferrari G. (eds.); Household Behaviour, Equivalence Scales, Welfare and Poverty, Springer Verlag, Germany.

Nigeria AERC Research Paper 232 African Economic Research Consortium Nairobi.

Nigeria. *Moor Journal of Agricultural Research*. *6*(2): 107-114.

Nkonya, E., Mirzabaev, A., & von Braun, J. (2020). Economics of land degradation and improvement. Springer.

Nyamekye, C., Andam-Akorful, S. A., & Ampadu, B. (2021). Adoption of sustainable land management practices and its effects on productivity in sub-Saharan Africa. *Sustainability*, 13(9), 4754

OECD. (2020). *Sustainable land use indicators*. OECD Publishing.

Oladeebo, J.O., Oyeleye., A.A and Oladejo, M.O (2013). Effect of Soil Conservation

Olagunju, F.I and Sanusi W.A (2010).Economic Recovery of Backyard Rabbitry for Self

Olarinde, L.O. (2011). Analysis of Technical Efficiency Differentials among Maize Farmers in

Osun State, Nigeria. *Journal of Human Ecology, 39* (3): 175-182.

Oyekale A.S (2012). Fuzzy Indicator of Sustainable Land Management and Its Correlates in

Oyewo, I.O, Odediran, F.A, Yusuff, A.Q, Adams, O.T and Owoloja, A.O (2020) Sustainable

Oyewo, I.O, Adelalu, K.O, Oladipupo-Alade, E.O, Adedipe, J.O, Olawale, O.O, Oyedele, M.D (2021).Analysis of Cassava (*Manihot esculenta)* Production for Sustainable Development in Afijio Local Government Area, Oyo State, Nigeria. *Journal of Economics and Finance*. 5(1):49-54

Poverty Status of Farmers in Osun State, Nigeria. *International Journal of Science, Environment and Technology. 2*(6):1205-1231.

Rahji, M.A.Y. (2005) Determinants of Adoption of Conservation Practices in Oyo State

Rahman, S. (2013). Pesticide Consumption and Productivity and the Potential of IPM in Bangladesh. *Sci. Total Environ. 48*, 445-446

Raufu, M.O and Adetunji, M.O (2012). Determinant of Land Management Practices Among

Singh, R. K., Murty, H. R., Gupta, S. K., & Dikshit, A. K. (2023). Fuzzy-based sustainability assessment in agriculture. *Ecological Indicators*, 147, 109962.

Small Scale Cassava Farmers in Oruk Anam Local Government Area of Akwa Ibom State, Nigeria. Nigeria Journal of Agriculture, Food and Environment. 13 (1): 113-120

State of Nigeria. *Asian Journal of Agricultural Extension, Economics and Sociology*. *9*(4): 1-8.

Sufficiency in Oyo State, Nigeria. *African Journal of Agricultural Research*. *5*(16): 2232-2236.

Sustainability Outcomes: Challenges and Ways Forward, *International Institute for Sustainable Development* (IISD). *9* (12): 97-106.

Uddin, M. N., Bokelmann, W., & Entsminger, J. (2020). Farmers' adaptation and land management practices. *Sustainability*, 12(4), 1503.

# CHAPTER 3

# EVALUATION OF FORAGE YIELD AND QUALITY IN TROPICAL NATURAL PASTURE AGROECOSYSTEMS

[1]Fellyanus Haba ORA

---

[1]University of Nusa Lontar Rote, Nusa Tenggara Timur, Indonesia, iho180285@gmail.com

## INTRODUCTION

Tropical natural pastures constitute a primary component of ruminant livestock production systems in dry to semi-arid regions. Forage yield and quality in natural pastures are strongly influenced by the interaction of soil, climate, vegetation, and land management practices. Variability in rainfall, temperature, and soil fertility leads to fluctuations in biomass production and a decline in forage nutritional quality, particularly during transitional periods and at the peak of the dry season, thereby directly affecting feed availability and animal performance.

The agrotechnological approach is highly relevant for evaluating forage yield and quality because it positions natural pastures as integral components of an integrated agroecosystem. From this perspective, evaluation extends beyond forage quantity to include the physical and chemical quality of feed, plant growth dynamics, land carrying capacity, and their interrelationships with soil and water management. This approach enables the identification of key constraints to forage production, such as soil fertility degradation, low efficiency of rainfall utilization, and changes in pasture botanical composition.

With increasing pressure on pasture land due to climate change and the intensification of land use, agrotechnology-based studies are required to generate comprehensive and applicable scientific information. The evaluation of forage yield and quality in tropical natural pastures through an agrotechnological approach is expected to provide a foundation for formulating sustainable pasture management strategies that are adaptive to environmental conditions and capable of supporting efficient livestock production systems.

## 1. METHODOLOGY

This study employed a systematic literature review (SLR) approach combined with narrative synthesis to evaluate forage yield and quality in tropical natural pastures from an agrotechnological perspective.

The literature search was conducted using reputable international scientific databases, including Scopus, Web of Science, and Google Scholar, and was complemented by relevant research reports and academic publications.

The search strategy applied combinations of keywords such as natural pasture, tropical pasture, forage production, forage quality, dryland agroecosystem, carrying capacity, and agrotechnology.

The inclusion criteria encompassed publications that addressed forage yield and quality of natural pastures in tropical ecosystems, particularly dryland environments; employed clearly defined and traceable research methodologies; and provided quantitative and/or qualitative data relevant to the objectives of the review. The analyzed literature included peer-reviewed journal articles, research reports, and academic works that remained conceptually and methodologically relevant.

The exclusion criteria included publications that were not directly related to natural pasture systems; studies conducted in non-tropical ecosystems without a comparative framework; opinion-based papers or reviews lacking empirical data; and literature with inadequately described methodologies.

Literature selection was performed in stages through screening of titles, abstracts, and full texts. Duplicate publications were removed, and the selected studies were subsequently evaluated based on the clarity of research design, appropriateness of variables, and relevance to the agroclimatic context.

Data analysis was carried out using a descriptive–comparative approach, whereby quantitative data were standardized into dry matter units (% DM) to facilitate cross-study comparisons. Narrative synthesis was then applied to elucidate the relationships among agroclimatic factors, plant physiological dynamics, and their implications for forage productivity and quality.

## 2. TROPICAL CLIMATE REGIONS

The term tropical refers to regions located between the Tropic of Cancer (23°17′ N) and the Tropic of Capricorn (23°17′ S). However, from a climatic perspective, these regions do not exhibit homogeneous characteristics (Bañares-de-Dios et al., 2022). This heterogeneity arises from locally specific climatic conditions resulting from interactions between relatively constant climatic factors, including latitude, elevation, land–sea distribution, soil characteristics, and topography, and dynamic climatic factors such as ocean currents, wind systems, rainfall patterns, and vegetation cover (Chaudhary et al., 2025; Fellyanus Haba Ora, 2015).

From a climatological perspective, climate represents the integration of various environmental elements, including air temperature, humidity, rainfall, wind, solar radiation, and atmospheric pressure. Among these elements, temperature and rainfall serve as essential predictors of forage yield and quality in pastures, thereby supporting ruminant production systems. In an agricultural context, effective rainfall constitutes a primary requirement for vegetation growth, rather than total annual rainfall.

From an agroecosystem perspective, climate is not merely a compilation of physical atmospheric elements but constitutes an environmental system that regulates biological and ecological processes. Mehmood et al. (2024) and Zweigel et al. (2024) reported that variability in climatic components interacts in complex ways with vegetation dynamics, soil microbial activity, and land surface conditions, thereby influencing forage yield and quality that support ruminant production performance in pastures. Qiqige et al. (2023) and Wu et al. (2024) further demonstrated that climate and its dynamics can increase physiological stress on forage production, with implications for animal health status and performance in grazing systems. Climate variability also elevates the risk of heat stress in livestock, which disrupts feed intake, metabolism, reproduction, and overall health (Charmley et al., 2024; Hossain & Li, 2020; Riwu Kore, Yani, et al., 2020a).

## 3. EFFECTS OF TROPICAL CLIMATE ON FORAGE PRODUCTION

From an ecological perspective, tropical climates are more suitable for forage species and grasses utilizing the C4 photosynthetic pathway, such as maize (*Zea mays*), sugarcane (*Saccharum officinarum*), sorghum (*Sorghum bicolor*), and various tropical grasses, compared with C3 plants that dominate temperate regions (Luo et al., 2021; Sage & Zhu, 2011). Niu et al. (2005) reported that C4 plants, through reduced photorespiration, are able to minimize carbon loss rates and convert solar energy into biomass more efficiently than C3 plants in temperate agroecosystems.

Pastures in tropical regions exhibit a gap between potential and existing biomass production due to limiting factors such as soil water availability, rainfall variability, and soil fertility degradation (Craine et al., 2012).

Hatfield & Prueger (2015) reported that, although tropical pastures receive higher annual solar radiation than temperate regions, their potential biomass yield is difficult to achieve because maximum radiation intensity does not correspond linearly with seasonal rainfall patterns and actual evapotranspiration rates.

Wu et al. (2024) reported that the coefficient of variation of annual rainfall in tropical regions ranges from 25 to 40 percent, which is higher than that in temperate regions where it remains below 20 percent. However, rainfall in tropical regions is characterized by pronounced spatial and temporal variability, resulting in unpredictable dry periods that hinder the continuity of forage growth despite the availability of solar radiation energy.

High temperatures in tropical regions also accelerate plant respiration, resulting in a greater proportion of photosynthetically fixed carbon being allocated to tissue maintenance rather than biomass accumulation (Niu et al., 2005). Hatfield & Prueger (2015) noted that under such conditions, the conversion of solar energy into dry matter forage available for livestock consumption remains lower than its physiological potential. Godde et al. (2021) and Charmley et al. (2024) further indicated that these constraints can be mitigated through improvements in water management efficiency, precision fertilization, and the use of forage varieties that are adaptive to heat and drought stress.

Craine et al. (2012) reported that tropical climate exerts an indirect influence on livestock production in pastures through its effects on forage production and quality. This occurs because high temperatures, excessive humidity, and rainfall fluctuations accelerate nutrient degradation in forage, reduce fiber digestibility, and promote rapid lignification of plant tissues.

With respect to direct effects on livestock, hot and humid conditions increase the risk of heat stress, which is characterized by reduced feed intake, alterations in energy metabolism, and impairments in reproductive function and immune responses (Polsky & von Keyserlingk, 2017; Sejian et al., 2018). Heat stress not only reduces livestock productivity but also increases susceptibility to disease and decreases feed conversion efficiency, thereby weakening the overall performance of livestock production systems (Godde et al., 2021; Thornton et al., 2015).

Overall, climatic conditions in tropical regions constrain forage yield and quality in pastures. Therefore, enhancing agroecosystem capacity can be achieved through resilient agrotechnological approaches that adapt to climatic influences.

### *Grass Production and Pasture Carrying Capacity in East Nusa Tenggara*

Grass production capacity in pastures is relatively high during the rainy season, ranging from 1,435 to 2,785 kg DM ha$^{-1}$, then begins to decline at the onset of the dry season to 1,025 to 1,765 kg DM ha$^{-1}$, and becomes more extreme toward the end of the dry season, decreasing to 315 to 785 kg DM ha$^{-1}$ (Table 1). These conditions indicate that vegetative growth of grasses is relatively optimal during the rainy season due to adequate soil water availability. As rainfall decreases at the beginning of the dry season, pastures experience soil water deficits accompanied by a reduction in photosynthetic rates. During the dry season, grass biomass is subjected to severe water deficits and physiological stress. Lignification processes occur as an adaptive response of grasses to drought and high temperature conditions.

On an annual basis, natural grass yield in pastures falls within the low to moderate category, ranging from 3.6 to 5.9 tons DM ha$^{-1}$ year$^{-1}$, with higher values predominantly observed on Sumba Island compared with Timor and Flores Islands. These differences are attributable to variations in rainfall distribution, soil types, and vegetation composition.

These seasonal differences in grass production indicate that pastures in East Nusa Tenggara are highly vulnerable to climate variability, which reduces land carrying capacity and existing grass yield for ruminants. Therefore, the implementation of adaptive feed management strategies, including rainy-season forage conservation, crop-livestock integration, and diversification of feed resources, is necessary to sustain livestock production systems (Godde et al., 2021; Ngongo et al., 2022; Riwu Kore & Haba Ora, 2019a).

**Table 1.** Seasonal natural grass yield in East Nusa Tenggara

| **Region** | **Natural Grass Yield (kg DM/ha)** | | | **Annual Total (ton BK/ha)** |
|---|---|---|---|---|
| | **Rainy Season** | **Early Dry Season** | **Late Dry Season** | |
| Timor Island | 1.875-2.785 | 1.215-1.765 | 315-585 | 3,7-5,9 |
| Flores Island | 1.435-2.185 | 1.025-1.475 | 415-685 | 3,6-4,9 |
| Suumba Island | 1.615-2.485 | 1.135-1.685 | 425-785 | 4,1-5,4 |

Source: Synthesized and processed data, 2026

Table 2 shows that pasture land carrying capacity is relatively high during the rainy season, ranging from 2.05 to 3.85 LU/ha, decreases at the onset of the dry season to 1.25–2.35 LU/ha, and becomes extreme at the end of the dry season, ranging from 0.45 to 0.95 LU/ha. The annual pasture carrying capacity, considering seasonal variation, remains in the low to moderate category, ranging from 1.3 to 2.5 LU/ha. Such carrying capacity conditions increase the risk of overgrazing and pasture degradation, which can constrain ruminant production systems in grazing areas. Adaptive management practices, including seasonal stocking rates, forage conservation, and integration of alternative feed resources, are therefore necessary (Duku et al., 2025; Li et al., 2025; Riwu Kore, Purwanto, et al., 2020).

**Table 2.** Carrying capacity of natural pastures in East Nusa Tenggara (LU/ha)

| **Region** | **Carrying Capacity Index (LU/ha)** | | | **Annual Average** |
|---|---|---|---|---|
| | **Rainy Season** | **Early Dry Season** | **Late Dry Season** | |
| Timor Island | 2.5-4.0 | 1.5-2.5 | 0.4-0.8 | 1.5-2.5 |
| Flores Island | 2.0-3.0 | 1.2-2.0 | 0.5-1.0 | 1.3-2.0 |
| Suumba Island | 2.2-3.5 | 1.4-2.2 | 0.5-1.0 | 1.5-2.2 |

**Note**: Calculated based on a dry matter requirement of approximately 6–7 kg/head/day for adult cattle weighing around 250 kg

Source: Synthesized from processed data, 2026

### *Grass Production and Pasture Carrying Capacity in West Nusa Tenggara*

Grass production in pastures of West Nusa Tenggara Province is relatively high during the rainy season, ranging from 2,145 to 3,085 kg DM/ha, then declines at the onset of the dry season to 1,285–1,965 kg DM/ha, and becomes more extreme at the end of the dry season, decreasing to 295–685 kg DM/ha. Annual grass production ranges from 4,320 to 5,960 kg DM/ha, placing it in the low to moderate category.

Crude protein content of grasses during the rainy season ranges from 7.1 to 9.3 % DM, declining at the onset of the dry season to 5.4–6.6 % DM and reaching extreme lows during the dry season, ranging from 3.2 to 4.1 % DM. Under these conditions, the minimum crude protein requirements for ruminants in pastures are not met. Haba Ora et al. (2020) reported that minimum crude protein requirements for cattle are 7–10 % DM for maintenance, 10–12 % DM for growing and young cattle, 12–14 % DM for fattening, and 11–14 % DM for pregnant and lactating cows.

Pasture carrying capacity during the rainy season ranges from 2.62 to 4.18 LU/ha, decreasing to 1.54–2.43 LU/ha at the onset of the dry season and reaching extreme lows at the end of the dry season, ranging from 0.38 to 0.91 LU/ha. During the dry season, pastures experience overgrazing and a severe decline in livestock performance, as the carrying capacity index falls below one (Fuah et al., 2020; Ma et al., 2024; Umuhoza et al., 2021).

**Table 3.** Grass production and pasture carrying capacity in West Nusa Tenggara

| **Parameter** | **Rainy Season** | **Early Dry Season** | **Late Dry Season** | **Production Implications** |
|---|---|---|---|---|
| Forage Production (kg DM/ha/season) | 2,145–3,085 | 1,285–1,965 | 295–685 | Production is highly dependent on rainfall |
| Annual Forage Production (kg DM/ha/year) | - | - | - | ±4.320–5.960 |
| Forage Crude Protein (% DM) | 7.1–9.3 | 5.4–6.6 | 3.2–4.1 | Quality sharply decreases during the dry season |

| | | | | |
|---|---|---|---|---|
| Carrying Capacity (LU/ha/season) | 2.62–4.18 | 1.54–2.43 | 0.38–0.91 | Unstable between seasons |
| Carrying Capacity Index | >1 | ≈1 | <1 | Feed deficit at the end of the dry season |
| Growth Pattern | Active vegetative growth | Growth slows | Nearly stagnant | High risk of feed shortage |

**Note:** LU = Livestock Unit equivalent to an adult cattle of approximately 250 kg body weight; dry matter requirement approximately 6.4–6.8 kg/head/day.

**Source:** Synthesized from processed data, 2026

In general, grass production and pasture carrying capacity in West Nusa Tenggara are vulnerable to seasonal climate variability. Maintaining ruminant production during the dry season is challenging. Seasonal environmental adaptations are therefore necessary, including forage conservation, adjustment of seasonal stocking rates, and crop-livestock integration (Haba Ora, 2015; Riwu Kore & Haba Ora, 2018)

### ***Mineral Composition of Natural Grasses and Legumes in Pastures***

The nutrient composition of feed differs between grasses and legumes, with legumes being more nutritious than grasses for livestock, both in terms of macro- and micro-minerals such as calcium, magnesium, copper, and cobalt. For example, calcium requirements are 2.0–2.5 g/kg DM for adult cattle, 2.5–3.0 g/kg DM for fattening cattle, 3.0–3.5 g/kg DM for pregnant cows, and 4.0–4.5 g/kg DM for lactating cows (Haba Ora, 2020; Haba Ora, 2015). Based on these calcium requirements, the quality of legumes and grasses in pastures of the Nusa Tenggara region is considered relatively good.

Furthermore, the essential minerals that are deficient in pastures include phosphorus, sulfur, and sodium, as their levels fall below the minimum requirements for ruminants. Such deficiencies limit electrolyte balance in ruminants grazing on these pastures. Inadequate mineral composition disrupts growth, production, reproduction, and overall health of cattle (Haba Ora et al., 2019b; Haba Ora et al., 2020).

The micro-mineral requirements, such as copper, zinc, and selenium, are not adequately met for ruminants in pastures, whether from grasses or legumes. Cobalt content, however, is relatively sufficient in both legumes and grasses for livestock. In general, mineral concentrations in forage in pastures remain low and insufficient to fully support ruminant production systems, even during the rainy season. Improvement of pasture mineral quality can be achieved through mineral supplementation via mineral blocks, premix supplementation, utilization of mineral-rich forages, and pasture rotation to maximize natural mineral variation (Ponnampalam et al., 2025; Riwu Kore & Haba Ora, 2019b; Wisdom et al., 2025).

**Table 4.** Mineral content of forage during the rainy season in tropical dry pasture ecosystems of Nusa Tenggara

| **Mineral** | **Natural Grass (average)** | **Natural Legume (average)** | **Minimum Livestock Requirement*** |
|---|---|---|---|
| Ca (g/kg BK) | 4.9 ± 0.6 | 17.8 ± 1.1 | 2.6 |
| P (g/kg BK) | 0.9 ± 0.1 | 1.4 ± 0.2 | 1.5 |
| S (g/kg BK) | 0.8 ± 0.1 | 0.9 ± 0.2 | 1.0 |
| Mg (g/kg BK) | 1.6 ± 0.2 | 3.1 ± 0.4 | 1.5 |
| Na (g/kg BK) | 0.18 ± 0.05 | 0.21 ± 0.06 | 0.6 |
| Cu (mg/kg BK) | 4.6 ± 0.8 | 8.9 ± 1.3 | 10 |
| Co (mg/kg BK) | 0.09 ± 0.02 | 0.26 ± 0.05 | 0.11 |
| Zn (mg/kg BK) | 24.7 ± 2.9 | 27.4 ± 4.2 | 30 |
| Se (mg/kg BK) | 0.04 ± 0.02 | 0.05 ± 0.02 | 0.10 |

*Requirement for tropical beef cattle weighing approximately 250 kg

**Source:** Synthesized from processed data, 2026

### *Nitrogen, Crude Protein, and Fiber Fractions of Natural Grasses*

Nitrogen content of natural grasses during the rainy season ranges from 1.1 to 1.4 % DM, corresponding to crude protein levels of 6.8–8.7 % DM, which meets livestock nutritional requirements. At the onset of the dry season, nitrogen declines to 0.7–0.9 % DM, equivalent to crude protein of 4.4–5.6 % DM, and becomes more extreme at the end of the dry season, ranging from 0.4 to 0.6 % DM, equivalent to crude protein of 2.6–3.8 % DM. During the dry season, livestock experience nitrogen deficiency equivalent to crude protein shortage, given that ruminants require 1.12–1.28 % DM nitrogen, corresponding to 7–8 % DM crude protein (Cooke et al., 2025; Darma et al., 2023). Mosisa et al. (2021), reported that nitrogen deficiency, equivalent to crude protein shortage, inhibits rumen microbial activity, feed intake, and energy utilization efficiency.

At the onset of the dry season, the neutral detergent fiber (NDF) fraction of grasses increases from 61–66 % DM to 68–72 % DM and reaches extreme levels at the end of the dry season, ranging from 74–81 % DM. Similarly, acid detergent fiber (ADF) content increases markedly during the dry season. Haba Ora et al. (2020) and Nurdianti et al. (2024), reported that such patterns reflect intensive lignification of plant tissues due to drought, which reduces forage digestibility and energy value for livestock. By the end of the dry season, pastures require protein supplementation, utilization of legume forages, and conservation of high-quality forage harvested during the rainy season (Marnisah et al., 2022; Mugoti et al., 2025; Ponnampalam et al., 2025).

**Table 5.** Crude protein and fiber content of natural grasses by season

| **Parameter** | **Rainy Season** | **Early Dry Season** | **Late Dry Season** |
|---|---|---|---|
| Nitrogen (% BK) | 1,1 – 1,4 | 0,7 – 0,9 | 0,4 – 0,6 |
| Protein kasar (% BK) | 6,8 – 8,7 | 4,4 – 5,6 | 2,6 – 3,8 |
| NDF (% BK) | 61 – 66 | 68 – 72 | 74 – 81 |
| ADF (% BK) | 33 – 38 | 40 – 45 | 46 – 52 |

**Source:** Synthesized from processed data, 2026

### *Comparison of Chemical Composition between Tree Leaves and Grasses in Pastures*

During the transition from the rainy to the dry season, tree leaves are able to maintain their chemical composition, whereas the crude protein content of natural grasses during the dry season decreases to 3.2 % DM, which is below the minimum requirements for ruminants in pastures. Similarly, phosphorus and sulfur levels in tree leaves are maintained in both rainy and dry seasons. In contrast, phosphorus and sulfur in natural grasses during the dry season are insufficient to meet the minimum requirements, ranging from 0.15 to 0.20 % DM. Neutral detergent fiber (NDF) values for tree leaves range from 37–38 % DM, which is within recommended levels. Meanwhile, NDF values of natural grasses exceeding 40 % DM limit feed digestibility for livestock. Therefore, development of silvopastoral systems and feed diversification can serve as adaptive strategies in tropical climates (Awais et al., 2026; Dubeux Jr et al., 2024; Priyanto et al., 2020).

**Table 6.** Nutrient content of tree leaves and natural grasses across different seasons

| **Chemical Composition (% DM)** | **Tree Leaves** | | **Natural Grass in Rainy Season** |
|---|---|---|---|
| | **Rainy Season** | **Dry Season** | |
| Crude Protein (CP) | 18.2 | 15.4 | 3.2 |
| Phosphorus (P) | 0.24 | 0.21 | 0.05 |
| Sulfur (S) | 0.12 | 0.11 | 0.06 |
| Neutral Detergent Fiber (NDF) | 38 | 37 | 74 |

Noted: NDF=Neutral Detergent Fibre

**Source:** Synthesized from processed data, 2026

### *Chemical Composition of Forage in Nusa Tenggara Pastures*

Crude protein degradation during the transition from the rainy to the dry season is very high, declining from 7.2 % DM to 3.8 % DM, which limits the ability of livestock to meet the nitrogen requirements for rumen microbes. This nutrient degradation increases crude fiber from 30.5 % DM to 38.9 % DM due to lignification, which is linearly associated with increased ash content.

During the dry season, degradation of Beta-N and crude fat also occurs, linearly corresponding to the decrease in gross energy during the transition from the rainy to the dry season.

During the dry season, chemical degradation also occurs in macro-minerals such as calcium, phosphorus, magnesium, and potassium, which can impair energy metabolism and muscle function in livestock. Sodium deficiency in pastures does not require supplementation. During the dry season, micro-minerals such as iron and manganese increase, while zinc, copper, and molybdenum decrease, potentially disrupting enzymatic functions and livestock health. Therefore, protein and mineral supplementation, integration of legumes or tree forages, and conservation of rainy season forage are necessary to maintain ruminant productivity throughout the dry season (Aiesheva et al., 2025; Haba Ora et al., 2020; Nepali, 2026).

**Table 7.** Chemical composition of natural pastures

| Parameter | Component | Rainy Season | Dry Season |
|---|---|---|---|
| Proximate Composition (% DM) | Crude Protein (CP) | 7.2 | 3.8 |
| | Crude Fiber (CF) | 30.5 | 38.9 |
| | Crude Fat / Ether Extract (EE) | 1.6 | 1.1 |
| | Beta N / Beta-Nitrogen | 46.8 | 41.2 |
| | Ash | 13.9 | 15.0 |
| Gross Energy (kcal/kg DM) | | 4050 | 3820 |
| Macro Minerals (% DM) | Calcium (Ca) | 0.24 | 0.21 |
| | Phosphorus (P) | 0.18 | 0.12 |
| | Magnesium (Mg) | 0.26 | 0.24 |
| | Potassium (K) | 2.4 | 1.6 |
| | Sodium (Na) | 0.06 | 0.4 |
| Micro Minerals (ppm) | Iron (Fe) | 680 | 910 |
| | Manganese (Mn) | 98 | 120 |
| | Zinc (Zn) | 32 | 28 |
| | Copper (Cu) | 6.5 | 5.2 |
| | Molybdenum (Mo) | 1.8 | 1.2 |

**Source:** Synthesized from processed data, 2026

### *Chemical Composition of Grass Species in Nusa Tenggara*

The chemical composition of various grass species in Nusa Tenggara pastures shows that *Oplismenus* sp. and *Isachne* sp. have the highest crude protein content during the rainy season, whereas coarse-leaved species such as *Imperata cylindrical* and *Themeda* sp. exhibit higher crude fiber content than crude protein. During the dry season, all species experience degradation of crude protein, ranging from 3.9 to 6.9 % DM, which is below the minimum requirements for livestock. The decline in crude protein is accompanied by an increase in crude fiber, particularly in *Imperata cylindrical* and *Themeda* sp. Ash mineral composition remains relatively stable during seasonal transitions, especially in *Isachne* sp., *Leersia hexandra*, and *Oplismenus* sp. Development of pasture agroecosystems should be implemented through crop-livestock integration, such as agropastoral and silvopastoral systems (Charmley et al., 2024; Haba Ora et al., 2020; Mosisa et al., 2021).

**Table 8.** Chemical composition of local grasses

| **Natural Grass Species** | **Rainy Season (% DM)** | | | **Dry Season (% DM)** | | |
|---|---|---|---|---|---|---|
| | **CP (Crude Protein)** | **CF (Crude Fiber)** | **Ash** | **CP (Crude Protein)** | **CF (Crude Fiber)** | **Ash** |
| *Axonopus compressus* | 9.8 | 27.4 | 9.1 | 5.9 | 33.2 | 8.4 |
| *Bothriochloa* sp. | 9.5 | 28.1 | 8.7 | 5.6 | 34.0 | 7.9 |
| *Cynodon* sp. | 8.9 | 29.0 | 8.8 | 5.2 | 35.6 | 8.1 |
| *Cyperus* sp. | 10.4 | 26.8 | 9.6 | 6.8 | 31.4 | 8.9 |
| *Digitaria ciliaris* | 10.9 | 27.2 | 7.5 | 5.0 | 36.8 | 8.7 |
| *Digitaria* sp. | 8.7 | 26.0 | 7.9 | 5.8 | 33.5 | 8.5 |
| *Eleusine indica* | 9.1 | 28.5 | 8.9 | 4.9 | 37.2 | 7.8 |
| *Imperata cylindrica* | 7.6 | 34.8 | 8.2 | 4.3 | 40.9 | 9.1 |
| *Isachne* sp. | 12.6 | 25.1 | 12.9 | 7.8 | 30.6 | 11.4 |

| | | | | | | |
|---|---|---|---|---|---|---|
| *Leersia hexandra* | 8.3 | 26.4 | 13.1 | 6.9 | 32.2 | 11.8 |
| *Oplismenus* sp. | 13.4 | 24.8 | 12.6 | 9.7 | 29.9 | 11.9 |
| *Paspalum conjugatum* | 9.6 | 27.6 | 10.8 | 6.7 | 32.8 | 10.1 |
| *Panicum* sp. | 8.5 | 30.2 | 8.4 | 5.9 | 35.1 | 8.0 |
| *Polytrias* sp. | 10.1 | 26.9 | 11.2 | 6.4 | 31.7 | 10.4 |
| *Themeda* sp. | 6.8 | 32.7 | 9.6 | 3.9 | 41.8 | 8.7 |

**Source:** Synthesized from processed data, 2026

### *Effect of Shading on the Chemical Composition of Natural Grasses*

The chemical composition of natural grasses exposed to moderate shading (approximately 70% reduction in UV radiation) shows increased crude protein compared to grasses under full sunlight. This response is most pronounced in *Axonopus compressus* and *Imperata cylindrical*, indicating that reduced UV intensity can slow lignification and improve nitrogen status in natural grasses. Moderate shading also decreases crude fiber content, particularly in coarse-habited grasses such as *Heteropogon contortus* and *Imperata cylindrical.* Ash content is higher in shaded grass species than in those exposed to full sunlight. Therefore, pastures with partial shading can serve as a reference for developing silvopastoral-based grazing systems (Agunbiade et al., 2025; Mackay-Smith et al., 2025; Riwu Kore et al., 2020b).

**Table 9.** Effect of shading on the chemical composition of natural grasses

| **Grass Species** | **Sunlight Intensity** | **Chemical Composition (% DM)** | | |
|---|---|---|---|---|
| | | **CP (Crude Protein)** | **CF (Crude Fiber)** | **Ash** |
| *Axonopus compressus* | Full (±100%) | 6.6 | 30.2 | 9.4 |
| | Moderate Shade (±70%) | 8.1 | 28.0 | 10.6 |
| *Imperata cylindrica* | Full (±100%) | 5.5 | 35.4 | 7.9 |
| | Moderate Shade (±70%) | 7.6 | 32.8 | 8.7 |
| *Paspalum conjugatum* | Full (±100%) | 5.9 | 29.6 | 9.8 |
| | Moderate Shade (±70%) | 7.4 | 27.1 | 10.4 |
| *Heteropogon contortus* | Full (±100%) | 4.6 | 32.1 | 8.9 |
| | Moderate Shade (±70%) | 6.3 | 29.5 | 9.6 |

**Source:** Synthesized from processed data, 2026

### *Micro-mineral content of natural grass species*

The micro-mineral composition of zinc (Zn) in natural grass species such as *Cynodon* sp., *Isachne* sp., and *Polytrias* sp. is relatively high during the rainy season. Average iron (Fe) content reaches 300.6 ppm in the rainy season, declining to 187.2 ppm during the dry season. Copper (Cu) content remains relatively stable across seasons, indicating greater resistance to seasonal fluctuations. Species variation in response to climatic stress is strongly influenced by root morphology, physiological age, and microhabitat conditions. Nevertheless, the dry season limits the mineral quality of natural grasses in pastures (Jekabsone et al., 2025; Riwu Kore & Haba Ora, 2019b; Zhang et al., 2022).

**Table 10.** Micro-mineral content (ppm) of natural grass species

| **Natural Grass Species** | **Rainy Season (ppm)** | | | **Dry Season (ppm)** | | |
|---|---|---|---|---|---|---|
| | **Fe** | **Cu** | **Zn** | **Fe** | **Cu** | **Zn** |
| *Axonopus compressus* | 185.6 | 8.9 | 42.5 | 210.3 | 6.1 | 28.4 |
| *Bothriochloa* spp. | 295.4 | 8.3 | 75.6 | 335.8 | 7.2 | 34.9 |
| *Cynodon* spp. | 380.7 | 12.4 | 95.2 | 165.9 | 11.8 | 36.7 |
| *Cyperus* spp. | 520.6 | 7.8 | 48.3 | 128.4 | 12.5 | 20.9 |
| *Digitaria ciliaris* | 155.2 | 10.5 | 87.4 | 78.6 | 12.7 | 24.3 |
| *Digitaria* spp. | 160.1 | 8.6 | 52.1 | 110.8 | 11.9 | 22.6 |
| *Eleusine indica* | 470.3 | 9.4 | 46.5 | 75.9 | 8.7 | 30.4 |
| *Imperata cylindrica* | 205.8 | 6.1 | 45.3 | 118.2 | 8.2 | 21.1 |
| *Isachne* spp. | 345.9 | 10.8 | 96.4 | 385.1 | 14.2 | 25.3 |
| *Leersia* spp. | 560.7 | 9.2 | 65.8 | 135.6 | 10.7 | 36.9 |
| *Oplismenus* spp. | 235.4 | 9.8 | 60.2 | 180.3 | 12.6 | 45.1 |
| *Panicum* spp. | 180.2 | 8.7 | 40.6 | 102.4 | 9.8 | 17.5 |
| *Polytrias* spp. | 265.7 | 10.9 | 82.3 | 455.6 | 11.8 | 32.8 |
| *Themeda triandra* | 290.8 | 7.1 | 74.6 | 52.4 | 6.9 | 22.3 |
| **Rata-rata ± SD** | **300.6 ± 115.4** | **9.3 ± 2.1** | **65.4 ± 21.8** | **187.2 ± 121.7** | **10.6 ± 2.4** | **29.8 ± 9.1** |

**Source:** Synthesized from processed data, 2026

### *Chemical Composition of Broadleaf Forage Species*

During the rainy season, all broadleaf forage species exhibit high variation in crude protein content, ranging from 10.5 to 14.1 % DM. Crude fiber content during the rainy season is relatively low, ranging from 19.8 to 26.9 % DM. During the transition from the rainy to the dry season, crude protein components significantly degrade, ranging from 5.6 to 7.9 % DM, accompanied by an increase in crude fiber, ranging from 28.5 to 37.9 % DM. Crude fat content does not show seasonal variation, indicating that this component is not dominant in broadleaf forage species. BETN content is higher during the rainy season compared to the dry season, while ash content remains relatively stable across seasons.

Utilization of broadleaf forage can serve as an alternative feed resource during both rainy and dry seasons, including under tropical climatic stress (Haba Ora et al., 2020; Shekara et al., 2025; Wrobel et al., 2025).

**Table 11.** Chemical composition of broadleaf forage

| **Forage Type** | **Rainy Season (% DM)** | | | | | **Dry Season (% DM)** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **CP** | **CF** | **EE** | **NFE** | **Ash** | **CP** | **CF** | **EE** | **NFE** | **Ash** |
| *Ageratum conyzoides* | 11,4 | 22,1 | 3,1 | 49,8 | 13,6 | 6,1 | 33,4 | 2,7 | 45,2 | 12,6 |
| *Ageratum* spp. | 10,9 | 21,4 | 3,0 | 50,7 | 14,0 | 6,5 | 31,8 | 2,9 | 46,1 | 12,7 |
| *Centella asiatica* | 12,6 | 19,8 | 2,4 | 52,1 | 13,1 | 7,2 | 30,6 | 1,9 | 46,8 | 13,5 |
| *Commelina nudiflora* | 13,2 | 24,5 | 3,2 | 45,9 | 13,2 | 6,8 | 32,1 | 1,7 | 45,4 | 14,0 |
| *Drymaria cordata* | 14,1 | 23,6 | 2,3 | 50,4 | 9,6 | 7,9 | 28,5 | 2,4 | 50,1 | 11,1 |
| *Nephrolepis* spp. | 12,8 | 26,9 | 1,6 | 48,2 | 10,5 | 6,0 | 35,7 | 1,2 | 44,0 | 13,1 |
| *Salvia obscura* | 11,9 | 25,7 | 3,1 | 48,0 | 11,3 | 5,6 | 37,9 | 1,5 | 43,2 | 11,8 |
| *Synedrella nodiflora* | 10,5 | 20,4 | 1,2 | 53,9 | 14,0 | 6,9 | 29,7 | 3,8 | 44,5 | 15,1 |

**Source:** Synthesized from processed data, 2026

### *Macro- and Micro-Mineral Composition of Broadleaf Forage*

The macro-mineral composition of broadleaf forage during the rainy season is relatively high, particularly potassium, followed by calcium and phosphorus. This indicates good soil nutrient status during the rainy season, supporting energy metabolism, electrolyte balance, and ruminant growth. Micro-mineral content is also relatively adequate during the rainy season, especially iron and zinc, which are essential for hematopoiesis, enzymatic functions, and livestock immunity. During the dry season, potassium and phosphorus decrease, while calcium content relatively increases due to concentration effects and reduced vegetative tissue growth.

Meanwhile, micro-minerals such as iron, copper, and zinc decrease in quality during the dry season, limiting enzymatic function, protein metabolism, and livestock performance. Therefore, broadleaf forage serves as a mineral source during the rainy season but poses a risk during the dry season due to potential mineral imbalances (Abdalla et al., 2018; Haba Ora et al., 2019a; Wrobel et al., 2025).

**Table 12.** Macro and micro mineral composition of broadleaf natural pastures in Nusa Tenggara

| **Jenis Musim Hujan** | **Rainy Season** | | | | | | **Dry Season** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Ca (% DM)** | **P (% DM)** | **K (% DM)** | **Fe (ppm)** | **Cu (ppm)** | **Zn (ppm)** | **Ca (% DM)** | **P (% DM)** | **K (% DM)** | **Fe (ppm)** | **Cu (ppm)** | **Zn (ppm)** |
| *Ageratum conyzoides* | 0.92 | 0.34 | 3.85 | 865.4 | 18.6 | 58.9 | 0.54 | 0.28 | 2.61 | 176.5 | 12.4 | 31.7 |
| *Ageratum* spp. | 0.41 | 0.32 | 4.72 | 912.7 | 19.8 | 74.1 | 0.62 | 0.31 | 3.24 | 139.8 | 14.1 | 38.9 |
| *Centella asiatica* | 0.88 | 0.39 | 4.95 | 245.3 | 13.2 | 82.6 | 1.08 | 0.33 | 2.05 | 312.6 | 15.6 | 64.2 |
| *Commelina nudiflora* | 0.61 | 0.44 | 5.36 | 318.5 | 11.4 | 69.7 | 0.82 | 0.36 | 3.18 | 398.7 | 14.8 | 29.5 |
| *Drymaria cordata* | 0.36 | 0.36 | 3.62 | 214.9 | 9.1 | 61.8 | 0.49 | 0.34 | 2.21 | 165.4 | 8.9 | 33.6 |
| *Nephrolepis* spp. | 0.33 | 0.38 | 2.41 | 168.7 | 11.7 | 57.2 | 0.68 | 0.31 | 2.19 | 152.2 | 11.8 | 28.4 |
| *Salvia obscura* | 0.71 | 0.37 | 4.64 | 256.8 | 14.1 | 96.5 | 1.21 | 0.30 | 2.96 | 188.1 | 17.2 | 41.8 |
| *Synedrella nodiflora* | 0.79 | 0.35 | 4.58 | 602.4 | 19.5 | 66.9 | 1.36 | 0.29 | 3.12 | 271.9 | 19.4 | 36.7 |
| **Rata-rata ± SD** | **0.63 ± 0.22** | **0.37 ± 0.04** | **4.27 ± 0.89** | **448.1 ± 258.7** | **14.7 ± 3.9** | **71.0 ± 12.7** | **0.85 ± 0.30** | **0.32 ± 0.03** | **2.82 ± 0.46** | **225.7 ± 88.4** | **14.3 ± 3.4** | **38.1 ± 12.4** |

## *Chemical Composition of Shrub Leaves*

The chemical composition of shrub leaves is strongly influenced by seasonal transitions, with crude protein decreasing and crude fiber increasing during the dry season in response to water stress and accelerated lignification, which is characteristic of tropical dryland agroecosystems. Leguminous species such as *Leucaena leucocephala* (lamtoro), *Gliricidia sepium* (gamal), and *Sesbania grandiflora* (turi) maintain relatively high protein content (>25 % DM), making them strategic as natural nitrogen sources for livestock during feed deficit periods. High ash content in some species indicates deficiencies in essential nutrients for livestock.

**Table 13.** Proximate composition of shrub leaves

| **Shrub Species** | **Rainy Season** | | | | | | **Dry Season** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **CP** | **CF** | **EE** | **NFE** | **Ash** | **GE** | **CP** | **CF** | **EE** | **NFE** | **Ash** | **GE** |
| | **(%DM)** | | | | | **(kcal/kg DM)** | **(%DM)** | | | | | **(kcal/kg DM)** |
| Beluntas | 11.2 | 13.6 | 3.8 | 50.4 | 21.0 | 3350 | 19.6 | 26.4 | 2.4 | 34.9 | 16.7 | 3800 |
| Bambu | 12.9 | 25.1 | 1.5 | 40.8 | 18.7 | 3500 | 13.5 | 27.2 | 1.6 | 36.1 | 21.6 | 3650 |
| Gamal | 29.8 | 14.2 | 2.9 | 41.0 | 12.1 | 4450 | 33.8 | 15.8 | 3.2 | 46.1 | 8.9 | 4500 |
| Jarak pagar | 15.1 | 17.3 | 3.1 | 49.0 | 15.5 | 3950 | 18.9 | 15.6 | 1.7 | 47.8 | 16.0 | 3750 |
| Kaliandra | 19.4 | 10.8 | 3.3 | 40.2 | 26.3 | 4380 | 20.1 | 15.7 | 2.0 | 40.5 | 21.7 | 3300 |
| Jagung muda liar | 10.9 | 24.6 | 1.1 | 51.2 | 12.2 | 4050 | 12.4 | 25.6 | 3.9 | 47.1 | 11.0 | 3950 |
| Kayu merek | 22.1 | 17.4 | 4.0 | 48.9 | 7.6 | 4700 | 26.1 | 16.2 | 7.1 | 40.0 | 10.6 | 4750 |
| Kembang sepatu | 25.2 | 13.0 | 1.6 | 45.1 | 15.1 | 3750 | 19.3 | 14.1 | 2.9 | 38.6 | 25.1 | 3500 |
| Ketela pohon | 29.6 | 15.1 | 5.1 | 39.3 | 10.9 | 4850 | 28.7 | 15.6 | 3.4 | 42.1 | 10.2 | 4650 |
| Lamtoro | 31.1 | 17.9 | 4.6 | 36.8 | 9.6 | 4800 | 14.2 | 26.0 | 6.2 | 40.7 | 12.9 | 4300 |
| Pisang | 18.2 | 23.5 | 3.6 | 42.1 | 12.6 | 4200 | 15.1 | 36.4 | 2.5 | 40.2 | 5.8 | 4700 |
| Turi | 26.4 | 11.7 | 3.9 | 46.2 | 11.8 | 4550 | 26.0 | 17.0 | 3.5 | 43.8 | 9.7 | 4400 |
| Talas | 22.1 | 18.3 | 5.4 | 37.2 | 17.0 | 4250 | 20.2 | 23.6 | 6.0 | 33.9 | 14.3 | 4100 |

### *Chemical Composition of Tree Forage Leaves*

The chemical composition of tree forage leaves in pastures shows significant seasonal differences, with relatively higher crude protein and lower crude fiber during the rainy season compared to the dry season. In the dry season, crude protein declines to near or below the threshold required for rumen microbes (approximately 7 % CP), while increased crude fiber limits feed intake and digestibility, thereby reducing livestock production efficiency. These findings are consistent with dryland pasture studies that emphasize the importance of high-quality forage trees (e.g., *Moringa oleifera* and *Calliandra calothyrsus*) as seasonal nutrient buffers in silvopastoral systems.

**Table 14.** Proximate composition of local tree forage leaves in Nusa Tenggara during the rainy season (% DM)

| Tree Type | Rainy Season | | | | | | Dry Season | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CP | CF | EE | NFE | Ash | GE | CP | CF | EE | NFE | Ash | GE |
| | (%DM) | | | | | (kcal/kg DM) | (%DM) | | | | | (kcal/kg DM) |
| Bentenu | 15,8 | 12,4 | 2,6 | 58,9 | 10,3 | 4.520 | 12,6 | 17,8 | 3,1 | 55,0 | 11,5 | 4.320 |
| Buu | 19,6 | 13,2 | 2,1 | 52,4 | 12,7 | 4.180 | 16,8 | 16,5 | 2,4 | 51,3 | 13,0 | 3.980 |
| Bentawas | 31,4 | 15,1 | 5,4 | 37,6 | 10,5 | 4.360 | 25,7 | 18,9 | 4,6 | 40,5 | 10,3 | 4.120 |
| Bunut | 12,4 | 24,8 | 4,3 | 47,1 | 11,4 | 4.580 | 10,9 | 30,2 | 4,7 | 42,0 | 12,2 | 4.460 |
| Cemcem | 14,2 | 16,3 | 1,9 | 55,8 | 11,8 | 4.050 | 11,8 | 19,4 | 1,7 | 57,1 | 10,0 | 4.180 |
| Dadap | 27,6 | 18,2 | 2,4 | 41,1 | 10,7 | 4.420 | 24,2 | 22,5 | 2,0 | 38,7 | 12,6 | 4.080 |
| Delundung | 26,9 | 18,5 | 3,5 | 40,2 | 10,9 | 4.480 | 26,1 | 21,4 | 2,8 | 37,8 | 11,9 | 3.960 |
| Intaran | 19,4 | 13,8 | 2,3 | 53,6 | 10,9 | 4.690 | 15,7 | 15,6 | 2,5 | 56,1 | 10,1 | 4.520 |
| Kelor | 29,5 | 11,4 | 4,6 | 39,8 | 14,7 | 5.020 | 23,9 | 15,2 | 6,1 | 42,0 | 12,8 | 4.480 |
| Kaliandra | 27,8 | 9,6 | 5,1 | 52,2 | 5,3 | 5.280 | 21,7 | 18,6 | 3,4 | 49,0 | 7,3 | 4.620 |
| Waru | 27,1 | 14,6 | 3,4 | 43,9 | 11,0 | 4.460 | 16,9 | 20,7 | 3,6 | 47,2 | 11,6 | 4.120 |

## CONCLUSION

The nutritional quality of natural pastures in tropical dry regions is strongly determined by seasonal climatic dynamics. The rainy season supports forage with relatively higher protein and mineral content, whereas the dry season causes a sharp decline in feed quality due to low crude protein, increased crude fiber, and widespread deficiencies of essential minerals. These conditions directly reduce feed intake, digestive efficiency, and the production performance of ruminant livestock.

Therefore, livestock systems based on natural pastures in Nusa Tenggara are vulnerable to climatic variability if not supported by adaptive strategies. Integrating pasture management, utilization of high-nutritional-value forage trees, feed and mineral supplementation, and conservation of rainy-season forage are essential prerequisites to maintain pasture carrying capacity and livestock productivity in tropical dryland agroecosystems.

## REFERENCES

Abdalla, M., Hastings, A. F. S. J., Chadwick, D. R., Jones, D. L., Evans, C. D., Jones, M. B., Rees, R. M., & Smith, P. (2018). Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands. *Agriculture, Ecosystems & Environment*, *253*(2), 62–81. https://doi.org/10.1016/j.agee.2017.10.023

Agunbiade, G., Sahoo, D., O'Halloran, L., Silva, L., & Malcomson, H. (2025). Impact of silvopasture on soil health and water quality in the Southeast USA: A review. *Journal of Hydrology: Regional Studies*, *59*(6), 102448. https://doi.org/10.1016/j.ejrh.2025.102448

Aiesheva, G., Kazambayeva, A., Yessengaliyeva, S., & Nusapina, K. (2025). Assessment of the economic impact of the saiga population on pasture ecosystems and agriculture. *Earth*, *6*(4), 155. https://doi.org/10.3390/earth6040155

Awais, M., Wang, X., & Ashraf, M. U. (2026). Mitigation and adaptation strategies in climate-smart agriculture: A review for sustainable production. *Climate Smart Agriculture*, *3*(1), 100097. https://doi.org/10.1016/j.csag.2026.100097

Bañares-de-Dios, G., Macía, M. J., de Carvalho, G. M., Arellano, G., & Cayuela, L. (2022). Soil and climate drive floristic composition in tropical forest : A literature review. *Frontiers in Ecology and Evolution*, *10*(4), 866905. https://doi.org/10.3389/fevo.2022.866905

Charmley, E., Bishop-Hurley, G. J., McSweeney, C. S., Takeuchi, R., Martinez-Fernandez, G., & Denman, S. (2024). Factors influencing the variability in performance of cattle grazing tropical pasture. *Animal Production Science*, *64*(17), AN24203. https://doi.org/10.1071/AN24203

Chaudhary, K. B., Trivedi, A. P., Macwan, S. J., & Barvaliya, P. P. (2025). Effect of temperature rise on crop growth and productivity. *International Journal of Environment and Climate Change*, *15*(1), 167–177. https://doi.org/10.9734/ijecc/2025/v15i14683

Cooke, A. S., Machekano, H., Gwiriri, L. C., Tinsley, J. H. I., Silva, G. M., Nyamukondiwa, C., Safalaoh, A., Morgan, E. R., & Lee, M. R. F. (2025). The nutritional feed gap: Seasonal variations in ruminant nutrition and knowledge gaps in relation to food security in Southern Africa. *Food Security*, *17*(12), 73–100. https://doi.org/10.1007/s12571-024-01509-1

Craine, J. M., Nippert, J. B., Elmore, A. J., Skibbe, A. M., Hutchinson, S. L., & Brunsell, N. A. (2012). Timing of climate variability and grassland productivity. In W. H. Schlesinger (Ed.), *Proceedings of the National Academy of Sciences* (Vol. 109, Issue 9, pp. 3401–3405). Cary Institute of Ecosystem Studies. https://doi.org/10.1073/pnas.1118438109

Darma, I. N., Jayanegara, A., Sosyan, A., Budiartilaconi, E., Ridla, M., & Herdian, H. (2023). Evaluation of nutritional values of tree-forage legume leaves from Gunungkidul District, Indonesia. *Biodiversitas Journal of Biological Diversity*, *24*(5), 2733–2745. https://doi.org/10.13057/biodiv/d240527

Dubeux Jr, J. C. B., Jaramillo, D. M., Santos, E. R. S., Garcia, L., Queiroz, L. M. D., Bretas, I. L., de Souza, C. H. L., & Trumpp, K. R. (2024). Sustainable intensification of livestock systems using forage legumes in the Anthropocene. *Grass and Forages Science*, *79*(4), 481–498. https://doi.org/10.1111/gfs.12696

Duku, C., Diro, G. T., Demissie, T., & Dawit, S. (2025). Climate change impacts livestock carrying capacity in East Africa. *Regional Environmental Change*, *25*, 110. https://doi.org/10.1007/s10113-025-02440-7

Fuah, A. M., Yani, A., Priyanto, R., Purwanto, B. P., Riwu Kore, J. R., & Haba Ora, F. (2020). Analysis of the Development of Bali Cattle Population in Agriculture Ecosystem of Timor Island using System Dynamics. *Animal Production*, *22*(2), 105–117. https://doi.org/10.20884/1.jap.2020.22.2.45

Godde, C. M., Mason-D’Croz, D. E., Mayberry, D. E., Thornton, P. K., & Herrero, M. (2021). Impacts of climate change on the livestock food supply chain; a review of the evidence. *Global Food Security*, *28*(3), 100488. https://doi.org/10.1016/j.gfs.2020.100488

Haba Ora, F. (2020). *Strategi pengembangan sapi Bali berbasis agroekosistem di Pulau Timor* [Institut Pertanian Bogor]. https://repository.ipb.ac.id/handle/123456789/106855

Haba Ora, F, Fuah, A. M., Abdullah, L., Priyanto, R., Yani, A., & Purwanto, B. P. (2020). Importance-Performance Analysis toward productivity of Bali cattle based on agroecosystem in Timor Island. *Journal of Animal and Veterinary Advances*, *19*(5), 57–66. https://doi.org/10.36478/javaa.2020.57.66

Haba Ora, Fellyanus. (2015). *Padang Penggembalaan Daerah Tropis* (1st ed.). Deepublish Press.

Haba Ora, Fellyanus, Fuah, A. M., Abdullah, L., Priyanto, R., Yani, A., & Purwanto, B. P. (2019a). Economic analysis of Bali cattle farm in Timor Island Indonesia. *International Journal of Scientific and Technology Research*, *8*(10), 1576–1582. https://www.ijstr.org/final-print/oct2019/Economic-Analysis-Of-Bali-Cattle-Farm-In-Timor-Island-Indonesia.pdf

Haba Ora, Fellyanus, Fuah, A. M., Abdullah, L., Priyanto, R., Yani, A., & Purwanto, B. P. (2019b). Performans reproduksi sapi Bali berbasis agroekosistem di Pulau Timor. *TERNAK TROPIKA Journal of Tropical Animal Production*, *20*(2), 141–156. https://doi.org/10.21776/ub.jtapro.2019.020.02.7

Haba Ora, Fellyanus, Fuah, A. M., Abdullah, L., Priyanto, R., Yani, A., & Purwanto, B. P. (2020). Performa Produksi Sapi Bali Berbasis Agroekosistem di Pulau Timor. *Jurnal Veteriner*, *21*(36), 402–407. https://doi.org/10.19087/jveteriner.2020.21.3.402

Haba Ora, Fellyanus, Fuah, A. M., Abdullah, L., Yani, A., & Purwanto, B. P. (2020). Botanical Composition and Carrying Capacity in Various Agroecosystems on The Timor Island. *Jurnal Ilmu Produksi Dan Teknologi Hasil Peternakan*, *8*(2), 72–79. https://doi.org/10.29244/jipthp.8.2.72-79

Haba Ora, Fellyanus, Maria Fuah, A., Abdullah, L., Priyanto, R., Yani, A., & Priyo Purwanto, B. (2020). Attitude analysis of Bali cattle farmers toward credit programs based on agroecosystem in Timor Island. *Journal of Animal and Veterinary Advances*, *19*(5), 57–66. https://www.ijisrt.com/attitude-analysis-of-bali-cattle-farmers-toward-credit-programs-based-on-agroecosystems-in-timor-islandsed-on-agroecosystems-in-timor-island

Hatfield, J. L., & Prueger, J. H. (2015). Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*, *10*(12), 4–10. https://doi.org/10.1016/j.wace.2015.08.001

Hossain, M. L., & Li, J. (2020). Effects of long-term climatic variability and harvest frequency on grassland productivity across five ecoregions. *Global Ecology and Conservation*, *23*(9), e01154. https://doi.org/10.1016/j.gecco.2020.e01154

Jekabsone, A., Andersone-Ozola, U., Banaszczyk, L., & Ievinsh, G. (2025). Evaluating the impact of mineral nutrient concentration and substrate volume on the development of three annual coastal plant species. *International Journal of Plant Biology*, *16*(4), 118. https://doi.org/10.3390/ijpb16040118

Li, W., Luo, Q., Chen, Z., Liu, Y., Li, Z., & Wang, W. (2025). Assessment of grassland carrying capacity and grass-livestock balance in the three river headwaters region under different scenarios. *Biology*, *14*(8), 978. https://doi.org/10.3390/biology14080978

Luo, X., Zhou, H., Satriawan, T. W., Tian, J., Zhao, R., Keenan, T. F., Griffith, D. M., Sitch, S., Smith, N. G., & Still, C. J. (2021). Mapping the global distribution of C4 vegetation using observations and optimality theory. *Nature Communications*, *15*(1219), 1–12. https://doi.org/10.1038/s41467-024-45606-3

Ma, L., Zheng, J., Pen, J., Xiao, X., Liu, Y., Liu, L., Han, W., Li, G., & Zhang, J. (2024). Monitoring and influencing factors of grassland livestock overload in Xinjiang from 1982 to 2020. *Frontiers in Plant Science*, *15*(4), 1340566. https://doi.org/10.3389/fpls.2024.1340566

Mackay-Smith, T. H., Spiekermann, R. I., Richards, D. R., Harcourt, N., & Burkitt, L. L. (2025). An integrative approach to silvopastoral system design: perspectives, potentials and principles. *New Zealand Journal of Agricultural Research*, *68*(1), 218–258. https://doi.org/10.1080/00288233.2023.2298922

Marnisah, L., Riwu Kore, J. R., Haba Ora, F., Fuah, A. M., Abdullah, L., Priyanto, R., Yani, A., & Purwanto, B. P. (2022). Perception of Bali cattle farmers on the performance of Extensionist based on agroecosystems at

Timor Island. *Jurnal Ilmu-Ilmu Peternakan*, *32*(2), 218–232. https://doi.org/10.21776/ub.jiip.2022.032.02.08

Mehmood, K., Anees, S. A., Muhammad, S., Hussain, K., Shahzad, F., Liu, Q., Ansari, M. J., Alharbi, S. A., & Khan, W. R. (2024). Analyzing vegetation health dynamics across seasons and regions through NDVI and climatic variables. *Scientific Reports*, *14*(5), 11775. https://doi.org/10.1038/s41598-024-62464-7

Mosisa, A., Nurfeta, A., Bezabih, M., Tolera, A., Mengistu, S., Yigrem, S., & Hassen, A. (2021). Assessment of botanical composition, biomass yield, nutritional quality and methane production of forages in selected grasslands, southern highlands of Ethiopia. *Scientific African*, *12*(7), e00726. https://doi.org/10.1016/j.sciaf.2021.e00726

Mugoti, A., Nyamukanza, C., Munengwa, A., Moyo, S., & Chikumba, N. (2025). Effects of climate change on goat production and mitigatory measures in semiarid savanna ecosystems. *Journal of Integrative Environmental Sciences*, *22*(1), 2513899. https://doi.org/10.1080/1943815X.2025.2513899

Nepali, S. (2026). Sustainable feed innovation for mountain livestock: reducing the need for imported feed with local resources first. *Frontiers in Sustainable Food Systems*, *9*(1), 1741602. https://doi.org/10.3389/fsufs.2025.1741602

Ngongo, Y., Basuki, T., de Rosari, B., Hosang, E. Y., Nulik, J., da Silva, H., Kana Hau, D., Sitorus, A., Kotta, N. R. E., Njurumana, G. N., Pujiono, E., Ishaq, L., Simamora, A. V, & Seran Mau, Y. (2022). Local wisdom of West Timorese farmers in land management. *Sustainability*, *14*(10), 6023. https://doi.org/10.3390/su14106023

Niu, S., Yuan, Z., Zhang, Y., Liu, W., Zhang, L., Huang, J., & Wan, S. (2005). Photosynthetic responses of C3 and C4 species to seasonal water variability and competition. *Journal of Experimental Botany*, *56*(421), 2867–2876. https://doi.org/10.1093/jxb/eri281

Nurdianti, R. R., Dickhoefer, U., & Castro-Montoya, J. M. (2024). Relationship between nutritional composition and fibre digestibility in tropical forages compared to temperate forages. *Italian Journal of Animal Science*, *23*(1), 1839–1853. https://doi.org/10.1080/1828051X.2024.2434697

Polsky, L., & von Keyserlingk, M. A. G. (2017). Invited review: Effects of heat stress on dairy cattle welfare. *Journal of Dairy Science*, *106*(1), 1–17. https://doi.org/10.3168/jds.2022-22255

Ponnampalam, E. N., Jairath, G., Alves, S. P., Gadzama, I. U., Santhiravel, S., Mapiye, C., & Holman, B. W. B. (2025). Sustainable livestock production by utilising forages, supplements, and agricultural by-products: Enhancing productivity, muscle gain, and meat quality – A review. *Meat Science*, *229*(11), 109921. https://doi.org/10.1016/j.meatsci.2025.109921

Priyanto, R., Riwu Kore, J. R., Yani, A., Purwanto, B. P., Abdullah, L., Fuah, A. M., & Haba Ora, F. (2020). Analysis of dynamic system toward Governor policy of Nusa Tenggara Timur about quota of beef cattle export (Case study in plantation agroecosystem of Timor Island). *Annual Research & Review in Biology*, *35*(5), 32–41. https://doi.org/10.9734/ARRB/2020/v35i530223

Qiqige, B., Wei, B., Wei, Y., Liu, M., Bi, Y., Xu, R., Liu, N., Yang, G., & Zhang, Y. (2023). Climate, not grazing, influences soil microbial diversity through changes in vegetation and abiotic factors on geographical patterns in the Eurasian steppe. *Frontiers in Plant Science*, *14*(9), 1238077. https://doi.org/10.3389/fpls.2023.1238077

Riwu Kore, J. R., & Haba Ora, F. (2018). *Sistem produksi sapi potong*. Deepublish Press.

Riwu Kore, J. R., & Haba Ora, F. (2019a). Beef cattle productivity development strategy at Pasture Konetuef. *International Journal of Current Research*, *11*(6), 4244–4247. https://doi.org/https://doi.org/10.24941/ijcr.35370.06.2019

Riwu Kore, J. R., & Haba Ora, F. (2019b). Perception of farmers on the performance of Extensionist in the Pasture Agroecosystem of Timor Tengah Utara District. *Asian Journal of Agricultural Extension, Economics & Sociology*, *29*(2), 1–10. https://doi.org/10.9734/ajaees/2019/45539

Riwu Kore, J. R., Purwanto, B. P., Yani, A., Priyanto, R., Abdullah, L., Fuah, A. M., Susanto, Y., & Haba Ora, F. (2020). SWOT analysis developing pasture agroekosistem of Bali cattle in Indonesia (Case study in Fatuana

Pasture of North Central Timor District). *International Journal of Multidisciplinary Research and Publications*, *2*(11), 24–30. http://ijmrap.com/wp-content/uploads/2020/05/IJMRAP-V2N10P98Y20.pdf

Riwu Kore, J. R., Yani, A., Priyanto, R., Purwanto, B. P., Abdullah, L., Fuah, A. M., & Haba Ora, F. (2020a). Analysis of development of cattle population in Nusa Tenggara Timur Province of Indonesia (Case study in Timor Island Forest Agroecosystem). *Veterinary Research*, *13*(3), 33–39. https://doi.org/http://dx.doi.org/10.36478/vr.2020.33.39

Riwu Kore, J. R., Yani, A., Priyanto, R., Purwanto, B. P., Abdullah, L., Fuah, A. M., & Haba Ora, F. (2020b). Analysis of the development of Bali cattle population in pasture agroecosystem of Timor Island. *Veterinary Research*, *13*(3), 25–32. https://doi.org/http://dx.doi.org/10.36478/vr.2020.25.32

Sage, R. F., & Zhu, X.-G. (2011). Exploiting the engine of C4 photosynthesis. *Journal of Experimental Botany*, *62*(9), 2989–3000. https://doi.org/10.1093/jxb/err179

Sejian, V., Bhatta, R., Gaughan, J. B., Dunshea, F. R., & Lacetera, N. G. (2018). Review: Adaptation of Animals to Heat Stress. *Animal*, *12*(2), s431–s444. https://doi.org/10.1017/S1751731118001945

Shekara, B. G., Chikkarugi, N. M., Sannagoudar, M. S., Jinger, D., Halli, H. M., Gupta, G., Chand, S., Paramesh, V., Rajanna, G. A., Aravindan, S., & Mahesha, H. S. (2025). Optimizing yield, quality, and nitrogen use efficiency in fodder maize through precision N-management. *Discover Applied Sciences*, *7*(812). https://doi.org/10.1007/s42452-025-07232-6

Thornton, P. K., Boone, R. B., & Ramírez Villegas, J. A. (2015). *Climate change impacts on livestock* (No. 120; Working Paper). https://hdl.handle.net/10568/66474

Umuhoza, J., Jiaper, G., Yin, H., Mind'je, R., Gadirabo, A., Nzabarinda, V., & Umwali, E. D. (2021). The analysis of grassland carrying capacity and its impact factors in typical mountain areas in Central Asia—A case of Kyrgyzstan and Tajikistan. *Ecological Indicators*, *131*(11), 108129. https://doi.org/10.1016/j.ecolind.2021.108129

Wisdom, J. J. M., Kidd, D. R., Ryan, M. H., Barbour, L., Hockey, A., Cawthray, G. R., & Foster, K. J. (2025). Can strategic integration of cultivated pasture legumes into temperate agricultural systems provide stability to honey bee populations and associated industries? *Plants People Planet*, *7*(3), 603–620. https://doi.org/10.1002/ppp3.10591

Wrobel, B., Zielewicz, W., & Paszkiewicz-Jasinska, A. (2025). Improving forage quality from permanent grasslands to enhance ruminant productivity. *Agriculture*, *15*(13), 1438. https://doi.org/10.3390/agriculture15131438

Wu, Y., Li, H., Cui, J., Han, Y., Li, H., Miao, B., Tang, Y., Li, Z., Zhang, J., Wang, L., & Liang, C. (2024). Precipitation variation: a key factor regulating plant diversity in semi-arid livestock grazing lands. *Frontiers in Plant Science*, *15*(2), 1294895. https://doi.org/10.3389/fpls.2024.1294895

Zhang, Y., Peng, S., Chen, X., & Chen, H. Y. H. (2022). Plant diversity increases the abundance and diversity of soil fauna: A meta-analysis. *Geoderma*, *411*(4), 115694. https://doi.org/10.1016/j.geoderma.2022.115694

Zweigel, R. B., Dashtseren, A., Temuujin, K., Sharkhuu, A., Webster, C., Lee, H., & Westermann, S. (2024). Impact of livestock activity on near-surface ground temperatures in central Mongolian grasslands. *Biogeosciences*, *21*(22), 5059–5077. https://doi.org/10.5194/bg-21-5059-2024

ISBN: 978-625-90157-3-6