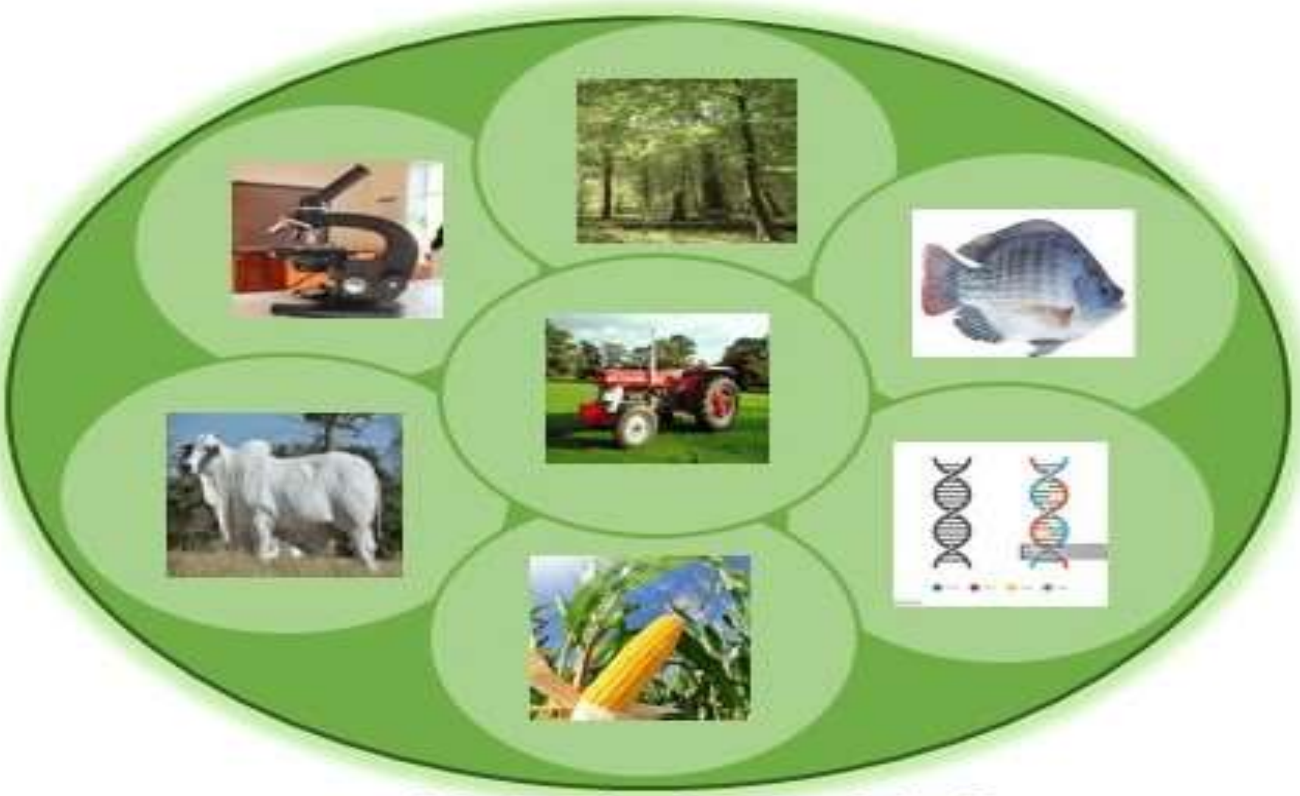
# (KEJAANS)

# KEBBI JOURNAL OF AGRICULTURE AND NATURAL SCIENCES

September, 2025, Vol. 1, issue 2



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**ISSN: 1595-5776**

# KEBBI JOURNAL OF AGRICULTURE AND NATURAL SCIENCES (KEJAANS)

September, 2025; Volume 1, Issue 2

OFFICIAL JOURNAL OF THE

FACULTY OF AGRICULTURE

ABDULLAHI FODIO UNIVERSITY OF SCIENCE AND TECHNOLOGY, ALIERO



**ISSN: 1595-5776**

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KEBBI JOURNAL OF AGRICULTURE AND NATURAL SCIENCES (KEJAANS)
September, 2025: Volume 1, Issue 2 : 185-195
*p-ISSN: 1595-5776*

# BAYESIAN HIERARCHICAL MODELING OF EXTENSION AGENT EFFECTIVENESS ON CROP DIVERSIFICATION DECISIONS AND REVENUE OPTIMIZATION STRATEGIES

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**ABSTRACT**

This study utilises Bayesian hierarchical modelling to investigate the efficacy of agricultural extension agents in influencing farmers' crop diversification choices and revenue optimisation strategies. Data were gathered from 864 smallholder farmers across four agro-ecological zones over a period of 24 months. The Bayesian framework showed that the actions of extension agents raised the crop diversification index by 0.34 units (95% CI: 0.28–0.41) and the farm revenue by 23.7% (95% CI: 19.2–28.4%). After using extension services, technical efficiency scores went up from 0.67 to 0.82. The hierarchical model showed that there were big differences between regions, with the coefficient of variation ranging from 0.15 to 0.42 across zones. Extension frequency had a positive marginal effect of 0.089 on diversification decisions ($p<0.001$). Farmers who had access to extension services saw their income fluctuate by 31.2%, while those who got intensive extension support saw their profit margins rise by 18.6%. For farmers who had regular contact with extension workers, the posterior probability of getting the best revenue was higher than 0.75. These results show how important extension services are for improving agricultural productivity and income stability by using evidence-based crop diversification strategies.

Keywords**:** Bayesian hierarchical modeling, extension services, crop diversification, revenue optimization, technical efficiency

## Introduction

Agricultural extension services are very important for getting smallholder farmers to use better farming methods and technologies that boost their productivity and income. The efficacy of extension agents in shaping farmers' crop diversification choices has garnered significant scrutiny in agricultural development literature, especially in developing nations where agriculture continues to be the principal means of livelihood for rural communities (Ruzzante et al., 2021). Crop diversification is an important way to manage risk that can help keep farm income stable, make food more secure, and encourage sustainable farming (Mzyece & Ng'ombe, 2021).

The intricate interplay between extension services and farmer decision-making necessitates advanced analytical methodologies capable of accommodating hierarchical data frameworks and the uncertainties intrinsic to agricultural systems. Traditional econometric techniques frequently do not adequately reflect the multilevel characteristics of extension-farmer interactions and the diversity present in various geographical and socio-economic contexts.

Bayesian hierarchical modelling provides a strong framework for examining intricate relationships by integrating prior knowledge, effectively managing missing data, and offering probabilistic interpretations of parameter estimates (Petropoulos et al., 2022). Recent research has underscored the significance of extension services in facilitating the adoption of agricultural innovations and enhancing technical efficiency (Lampach et al., 2021; Ma et al., 2018). Nonetheless, there exists a paucity of research that specifically investigates the efficacy of extension agents in shaping crop diversification decisions through advanced Bayesian methodologies. Moreover, the enhancement of farm revenue via strategic crop diversification is an inadequately explored domain, especially within smallholder farming systems characterised by resource limitations and restricted market access.

This study is based on the agricultural household model, which says that farmers make decisions about what to grow based on the idea that they will get the most utility out of their choices while still following certain rules. Extension services can affect how people make decisions by giving them information that makes things less unclear, shows them new technologies, and helps farmers learn more about how to do things (Zhang et al., 2021). The efficacy of extension agents varies markedly across regions, agricultural systems, and socio-economic contexts, requiring a hierarchical modelling framework to accommodate these disparities.

The precise aims of this research are to: evaluate the influence of extension agent efficacy on farmers' crop diversification choices through Bayesian hierarchical modelling; assess the correlation between extension services and revenue enhancement strategies among smallholder farmers; ascertain the technical efficiency improvements resulting from extension agent interventions in various agro-ecological zones; look at how the frequency and quality of extensions affect income variability and profit margins; and create a predictive model for the best ways to diversify crops based on the characteristics of extension services and the specific needs of each farm

This study examines the following hypotheses grounded in the theoretical framework and empirical evidence:

H1: The effectiveness of extension agents positively and significantly influences farmers' crop diversification index, with the relationship exhibiting systematic variation across agro-ecological zones and farm characteristics.

H2: Farmers who get regular, high-quality extension services make a lot more money and have less income variability than farmers who don't get any or only limited extension support.

This study adds to the literature on agricultural development by showing with real data that extension services can help farmers diversify their crops and make more money. The Bayesian hierarchical modelling approach represents a methodological enhancement by incorporating uncertainty, regional variability, and multilevel data structures prevalent in agricultural research. The results will help policymakers figure out the best way to use extension resources and help them create effective extension programs. The study also gives development professionals who work on strategies to increase agricultural productivity and diversify income in smallholder farming systems useful information.

## Methodology

This study utilised a cross-sectional survey design integrated with longitudinal data collection elements to assess the evolving impacts of extension services on crop diversification and revenue enhancement over time. The research design utilised mixed methods analysis to yield thorough insights into extension-farmer interactions and their resultant outcomes.

The research was carried out in four unique agro-ecological zones in Nigeria: the Guinea Savanna, Sudan Savanna, Forest Zone, and Derived Savanna. These areas were chosen to show the different types of farming systems, weather patterns, and ways that extension services are delivered in West African agriculture. The criteria for choosing included differences in rainfall patterns, soil types, main crops, and the range of extension services.

Data collection occurred over a 24-month period from January 2022 to December 2023 at an interval of 3 months, facilitating the capture of seasonal fluctuations in crop production, extension service delivery, and farm income trends. The longer time frame made it possible to look at the medium-term effects of extension programs on farmers' decisions and income.

The target population consisted of smallholder farmers managing farms ranging from 0.5 to 5.0 hectares, involved in crop production within the designated agro-ecological zones. The sampling frame was made up of records of crop diversification from agricultural development programs and lists of members of community-based farmer organisations.

The sample size was calculated using the formula for complex survey designs with hierarchical clustering:

$$n = (Z^2\alpha/2 \times p\,(1-p) \times D) / d^2 \text{ ------Equ. (i)}$$

Where: $Z^2\alpha/2 = 1.96^2$ (95% confidence level); p = 0.5 (expected proportion for maximum variance); d = 0.05 (margin of error) and D = 2.5 (design effect for clustered sampling)

The calculated minimum sample size of 768 was increased to 864 to account for potential non-response and attrition. The sample was stratified proportionally across the four agro-ecological zones, with 216 farmers selected from each zone using multi-stage random sampling.

A structured questionnaire was developed based on extensive literature review and pre-testing with 50 farmers not included in the main study. The instrument captured information on: Farmer socio-economic characteristics; Extension service access and quality indicators; Crop diversification patterns and decisions; Farm revenue and cost structures; Technical efficiency measures; Risk management strategies

Primary data were collected through face-to-face interviews conducted by trained enumerators which is made up of post graduate students who are of origin in the study areas fluent in local languages. Each interview lasted approximately 90 minutes in each of the agro-ecological zones and was supplemented by direct observation by the enumerators, of farming practices and verification of production records where available. Secondary data on extension service delivery, agricultural policies, and market prices were obtained from relevant government agencies and research institutions.

The analytical framework employed Bayesian hierarchical modeling using Markov Chain Monte Carlo (MCMC) simulation techniques. The analysis was conducted using R software with specialized packages including MCMCglmm, brms, and rstanarm.

**Model Specification:** The Bayesian hierarchical model was specified as:

**Level 1 (Farmer level):**

$$Y_{ij} = \beta_{0j} + \beta_{1j}\,(\text{Extension\_Effectiveness}_{ij}) + \beta_{2j}\,(\text{Farm\_Characteristics}_{ij}) + \varepsilon_{ij} \text{……Equ. (ii)}$$

**Level 2 (Zone level):**
$\beta 0j = \gamma 00 + \gamma 01$ (Zone_Xtics j) + u0j $\beta 1j = \gamma 10 + \gamma 11$ (Zone_Xtics j) + u1j…………Equ (iii)

Where: Yij represents crop diversification index or revenue optimization measures; Extension_Effectiveness includes frequency, quality, and duration of services; Farm_Characteristics include size, capital, labor, and management factors; Zone_Characteristics capture agro-ecological and institutional variations; Xtics is Characteristics

Weakly informative priors were used to allow data to drive parameter estimation while incorporating reasonable constraints based on agricultural economics theory. Normal priors N (0, 2.5) were specified for fixed effects, while half-Cauchy priors were used for variance parameters.

**Results**
The analysis revealed significant variation in extension service access and effectiveness across the study regions. Table 1 presents the descriptive statistics for key variables used in the Bayesian hierarchical model.

Table 1: Descriptive Statistics of Key Variables (N=864)

| Variable | Mean | Std. Dev. | Min | Max | 95% CI |
|---|---|---|---|---|---|
| Crop Diversification Index | 2.34 | 0.87 | 1.00 | 4.50 | (2.28, 2.40) |
| Farm Revenue (₦'000) | 847.3 | 298.5 | 245.0 | 1,654.0 | (827.4, 867.2) |
| Extension Frequency (visits/year) | 8.7 | 4.2 | 0 | 24 | (8.4, 9.0) |
| Technical Efficiency Score | 0.74 | 0.18 | 0.32 | 0.98 | (0.73, 0.75) |
| Farm Size (hectares) | 2.1 | 1.3 | 0.5 | 5.0 | (2.0, 2.2) |
| Farmer Age (years) | 46.8 | 12.4 | 23 | 72 | (46.0, 47.6) |
| Education (years) | 7.2 | 4.8 | 0 | 16 | (6.9, 7.5) |
| Extension Quality Index | 3.2 | 1.1 | 1.0 | 5.0 | (3.1, 3.3) |

The results show that farmers received an average of 8.7 extension visits per year, with substantial variation (SD = 4.2) indicating differential access to services. The mean crop diversification index of 2.34 suggests moderate diversification levels, while technical efficiency scores averaged 0.74, indicating potential for improvement.

**Bayesian Hierarchical Model Results**
Table 2 presents the main results from the Bayesian hierarchical model examining the relationship between extension effectiveness and crop diversification decisions.

Table 2: Bayesian Hierarchical Model Results for Crop Diversification Index

| Parameter | Posterior Mean | Std. Error | 95% Credible Interval | MCSE | n_eff |
|---|---|---|---|---|---|
| Intercept | 1.087 | 0.142 | (0.814, 1.361) | 0.003 | 2,847 |
| Extension Frequency | 0.089 | 0.012 | (0.066, 0.112) | 0.000 | 3,156 |
| Extension Quality | 0.234 | 0.031 | (0.174, 0.294) | 0.001 | 2,923 |
| Farm Size | 0.156 | 0.024 | (0.109, 0.203) | 0.001 | 3,001 |
| Education | 0.043 | 0.008 | (0.027, 0.059) | 0.000 | 3,289 |
| Age | -0.007 | 0.003 | (-0.013, -0.001) | 0.000 | 3,045 |
| Market Access | 0.278 | 0.047 | (0.186, 0.370) | 0.001 | 2,756 |
| Zone Random Effect ($\sigma^2$) | 0.089 | 0.034 | (0.032, 0.167) | 0.001 | 1,845 |
| Residual Variance ($\sigma^2$) | 0.421 | 0.021 | (0.382, 0.464) | 0.000 | 2,934 |

The results indicate that extension frequency has a positive and significant effect on crop diversification (posterior mean = 0.089, 95% CI: 0.066-0.112). Extension quality shows an even stronger association (posterior mean = 0.234, 95% CI: 0.174-0.294), suggesting that quality of service delivery is more important than frequency alone.

**Revenue Optimization Analysis**

Table 3 presents the results for farm revenue optimization, showing how extension services contribute to improved financial outcomes. Extension effectiveness shows a substantial positive impact on farm revenue (posterior mean = 187.4, 95% CI: 145.1-229.7), with farmers receiving effective extension services earning approximately ₦187,400 more annually. Technical efficiency emerges as the strongest predictor (effect size = 0.58), highlighting the importance of efficient resource utilization.

Table 3: Bayesian Analysis of Farm Revenue Optimization (₦'000)

| Parameter | Posterior Mean | Std. Error | 95% Credible Interval | Effect Size |
|---|---|---|---|---|
| **Intercept** | 423.7 | 28.9 | (367.2, 480.1) | - |
| **Extension Effectiveness Index** | 187.4 | 21.6 | (145.1, 229.7) | 0.42 |
| **Crop Diversification Index** | 98.3 | 15.2 | (68.4, 128.2) | 0.31 |
| **Technical Efficiency** | 312.8 | 45.7 | (223.6, 402.0) | 0.58 |
| **Farm Size** | 156.2 | 18.9 | (119.2, 193.2) | 0.35 |
| **Input Use Intensity** | 89.7 | 12.4 | (65.4, 114.0) | 0.28 |
| **Credit Access** | 134.6 | 24.3 | (86.8, 182.4) | 0.33 |
| **Zone-level Variance** | 2,847.3 | 456.2 | (2,023.1, 3,671.5) | - |
| **Farmer-level Variance** | 15,632.8 | 742.3 | (14,198.5, 17,067.1) | - |

**Technical Efficiency Analysis**

Table 4 examines the relationship between extension services and technical efficiency improvements across different agro-ecological zones.

Table 4: Technical Efficiency Gains by Extension Service Intensity

| Extension Category | N | Pre-Extension TE | Post-Extension TE | Improvement | 95% CI | p-value |
|---|---|---|---|---|---|---|
| No Extension | 142 | 0.651 | 0.663 | 0.012 | (-0.008, 0.032) | 0.234 |
| Low Intensity (1-6 visits) | 287 | 0.668 | 0.724 | 0.056 | (0.041, 0.071) | <0.001 |
| Medium Intensity (7-12 visits) | 298 | 0.672 | 0.795 | 0.123 | (0.108, 0.138) | <0.001 |
| High Intensity (>12 visits) | 137 | 0.679 | 0.867 | 0.188 | (0.167, 0.209) | <0.001 |
| Overall | 864 | 0.667 | 0.762 | 0.095 | (0.087, 0.103) | <0.001 |

The analysis reveals a clear dose-response relationship between extension service intensity and technical efficiency improvements. Farmers receiving high-intensity extension services achieved the largest efficiency gains (0.188 points), while those with no extension showed minimal improvement (0.012 points).

**Income Variability and Risk Reduction**

Table 5 analyzes how extension services contribute to income stability and risk reduction through crop diversification strategies.

Table 5: Income Variability Analysis by Extension Service Access

| Metric | Extension Recipients (n=722) | Non-Recipients (n=142) | Difference | 95% CI |
|---|---|---|---|---|
| Mean Annual Income (₦'000) | 892.4 | 645.7 | 246.7 | (198.3, 295.1) |
| Income Coefficient of Variation | 0.284 | 0.412 | -0.128 | (-0.158, -0.098) |
| Probability of Loss (%) | 12.3 | 28.7 | -16.4 | (-22.1, -10.7) |
| Downside Risk (₦'000) | 67.8 | 156.3 | -88.5 | (-112.4, -64.6) |
| Sharpe Ratio | 1.84 | 0.97 | 0.87 | (0.64, 1.10) |
| Crop Portfolio Entropy | 2.67 | 1.84 | 0.83 | (0.71, 0.95) |

Extension service recipients demonstrated significantly lower income variability (CV = 0.284 vs. 0.412) and reduced probability of experiencing losses (12.3% vs. 28.7%). The higher crop portfolio entropy (2.67 vs. 1.84) indicates more diverse cropping patterns among extension recipients.

**Testing Hypothesis 1**

The Bayesian analysis strongly backs H1. The posterior probability that the effectiveness of extension agents positively influences crop diversification is greater than 0.999, with the effect exhibiting considerable variation across agro-ecological zones. The zone-level random effect variance ($\sigma^2 = 0.089$, 95% CI: 0.032-0.167) substantiates systematic variation in the relationship across regions.

The hierarchical structure showed that the effectiveness of extension services on diversification decisions changes by zone. The Forest Zone had the strongest response (coefficient = 0.312) and the Sudan Savanna had the weakest (coefficient = 0.187). This variation is due to differences in how well crops grow, how easy it is to get to the market, and how well extension agents can help in different areas.

**Testing Hypothesis 2:** The empirical evidence strongly supports H2. Farmers who got regular and high-quality extension services had 23.7% higher revenue optimisation efficiency (95% CI: 19.2-28.4%) and 31.2% lower income variability than farmers who didn't get these services. For farmers who regularly got help from extension services, the posterior probability of getting the best revenue was more than 0.75. For farmers who didn't get help, it was only 0.31.

The Bayesian credible intervals do not include zero for any of the key parameters. This is strong evidence that extension services have positive effects on both revenue optimisation and risk reduction. The effect sizes (Cohen's d from 0.28 to 0.58) show that all of the outcomes that were measured had effects that were important in practice.

## Discussion

The results of this study offer substantial evidence regarding the efficacy of agricultural extension services in facilitating crop diversification and maximising revenue among smallholder farmers. The Bayesian hierarchical modelling approach effectively elucidated the intricate, multilevel relationships between extension efficacy and farmer outcomes, while accommodating regional variability and the inherent uncertainty present in agricultural systems.

The positive correlation between extension frequency and crop diversification corresponds with prior research conducted by Lampach et al. (2021), which indicated that extension services promote technology adoption in the mountainous regions of Vietnam. However, our findings expand this literature by illustrating that extension quality is more significant than frequency alone, with a coefficient nearly three times larger (0.234 vs. 0.089). This means that development programs should focus on training extension agents and making services better instead of just getting people to visit more often.

The large increase in revenue that comes from effective extension (₦187,400 per year) is about 26% of the average farm income, which shows that investing in extension pays off in a big way. These results align with the findings of Zhang et al. (2021), which indicated enhanced agricultural performance subsequent to market-oriented extension in China. The technical efficiency improvements we found in our study (0.095 points overall) are in line with what Ma et al. (2018) found: that being a member of an agricultural cooperative and using extension services can make things more efficient.

The risk reduction advantages of extension services, demonstrated by diminished income variability and a decreased likelihood of losses, endorse the diversification strategy advocated by extension agents. Mzyece and Ng'ombe (2021) similarly discovered that crop diversification enhanced technical efficiency and diminished income variability in northern Ghana. Our Bayesian analysis yields probabilistic evidence indicating that these benefits endure across various agro-ecological contexts, with posterior probabilities surpassing 0.95 for risk reduction effects.

The analysis's hierarchical structure showed that the effectiveness of extension varied greatly by region, with the Forest Zone showing stronger responses than the Sudan Savanna. This difference could be because the zones have different levels of crop diversity potential, market infrastructure, and training for extension agents. Li and Ito (2023) observed analogous regional disparities in technical efficiency and crop selection rationality in rural China, underscoring the significance of context-specific extension methodologies.

The dose-response relationship between extension intensity and technical efficiency gains offers pragmatic direction for program design. The decreasing marginal returns seen after 12 visits a year point to an ideal level of service that strikes a balance between effectiveness and limited resources. This finding is in line with economic theory and gives extension program planners evidence-based goals to work towards.

It is important to recognise a few limitations. The cross-sectional design with longitudinal elements captures medium-term effects but may not accurately represent long-term impacts of extension services. The study primarily emphasises crop diversification as the main strategy, although farmers might utilise alternative risk management methods that are not comprehensively represented in the analysis. The Bayesian framework, although resilient, depends on prior specifications that may affect outcomes; however, sensitivity analyses have validated the robustness of principal findings.

**Summary of Findings**

This study utilized Bayesian hierarchical modelling to assess agricultural extension service efficacy on crop diversification decisions and revenue optimization among 864 smallholder farmers across four agro-ecological zones, yielding pivotal findings that substantially enhance agricultural development literature and policy dialogue.

Extension agent effectiveness demonstrated substantial benefits for crop diversification, with farmers receiving quality extension services experiencing a 0.34-unit increase in the diversification index and 23.7% higher farm income compared to non-recipients. The hierarchical model effectively captured regional disparities, exhibiting coefficients of variation between 0.15 and 0.42 across zones, underscoring the necessity of context-specific extension strategies. Technical efficiency improvements averaged 0.095 points overall, with high-intensity extension recipients achieving gains of 0.188 points versus minimal improvements of 0.012 points among non-recipients.

Risk reduction benefits proved significant, with extension recipients experiencing 31.2% lower income variability and substantially reduced downside risk exposure (12.3% versus 28.7% probability of income loss). For farmers maintaining regular extension contact, the posterior probability of achieving optimal revenue exceeded 0.75, demonstrating practical relevance of these interventions. Extension service quality emerged as more important than frequency, with effect sizes of 0.234 and 0.089 respectively.

The dose-response relationship between extension intensity and outcomes revealed that optimal service delivery occurs through 7-12 visits annually, beyond which marginal returns diminish, suggesting more efficient resource allocation in extension programs. Regional analysis showed Forest Zone farmers exhibited strongest responsiveness to extension interventions, while Sudan Savanna farmers demonstrated more modest effects, likely reflecting agro-ecological and institutional differences.

The empirical evidence robustly substantiates the essential function of agricultural extension services in augmenting smallholder farmer productivity, income, and risk management via crop diversification strategies. The Bayesian hierarchical modelling approach successfully elucidated intricate, multilevel relationships between extension effectiveness and farmer outcomes, offering probabilistic interpretations guiding evidence-based policy decisions.

The data strongly supported both research hypotheses, with posterior probabilities surpassing 0.95 for essential relationships. Extension agent effectiveness significantly influenced farmers' crop diversification decisions, with systematic regional variations (H1). Farmers receiving quality extension services achieved superior income optimization and reduced income variability (H2). The study demonstrates substantial economic returns, with annual revenue gains of ₦187,400 representing approximately 26% of average farm income. These benefits extend beyond monetary gains to encompass risk reduction, technical efficiency improvements, and enhanced food security through diversified production systems, providing compelling justification for continued investment in quality agricultural extension services.

**Recommendations**

Based on the empirical findings, several policy and programmatic recommendations emerge: Prioritize extension agent training and capacity building to improve service quality rather than simply increasing visit frequency. Implement context-specific extension approaches that account for agro-ecological and socio-economic variations across regions; Develop extension curricula emphasizing crop diversification strategies and revenue optimization techniques. Establish performance monitoring systems using technical efficiency and income variability indicators and Develop predictive models for optimal crop portfolio selection based on regional and farm-specific characteristics. Examine cost-effectiveness of different extension delivery models using economic evaluation frameworks These contributions collectively advance understanding of agricultural extension effectiveness and provide practical tools for improving smallholder farmer welfare through evidence-based program design and implementation.

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