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REVIEW

Addressing Nutritional Challenges through Agricultural Extension: A Comprehensive Systematic Review of Nutrition-Sensitive Interventions

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Abstract

The global nutrition crisis, characterized by the triple burden of undernutrition, micronutrient deficiencies, and obesity-related non-communicable diseases, poses a systemic challenge to human health and sustainable development, particularly in low- and middle-income countries (LMICs). Agricultural extension services (AES), traditionally focused on productivity, are increasingly pivotal in delivering nutrition-sensitive agriculture (NSA) interventions to address these issues. This systematic review synthesizes evidence from 42 studies (2015–2025) to evaluate the effectiveness of NSA through AES, with a focus on dietary diversity, micronutrient status, and food security in LMICs. Key findings highlight the efficacy of nutrition education, biofortification, gender-sensitive strategies, digital innovations, and policy coherence in improving nutritional outcomes. Successful cases—such as Rwanda's Home Garden Program, India's Nutrition Gardens, and Uganda's biofortification efforts—demonstrate AES's transformative potential when integrated with multisectoral approaches. However, challenges, including resource scarcity, cultural resistance, and fragmented policies, persist, alongside research gaps in the longitudinal impacts and urban-rural dynamics. Recommendations include capacity building, technological scaling, and policy alignment to embed AES within national nutrition frameworks, advancing Sustainable Development Goal 2 (Zero Hunger). This review highlights AES as a critical lever in the agriculture-nutrition nexus, offering scalable strategies to nourish populations sustainably.

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Statement of Sustainability: This systematic review pioneers a comprehensive evaluation of nutrition-sensitive agriculture (NSA) through agricultural extension services (AES), uniquely synthesizing 42 studies to highlight scalable interventions like biofortification and digital innovations. Addressing dietary diversity, micronutrient deficiencies, and food security in LMICs directly advances SDG 2 (Zero Hunger). Its emphasis on gender equity and policy coherence further supports SDG 5 (Gender Equality) and SDG 17 (Partnerships for the Goals). The work's novelty lies in its holistic integration of education, technology, and multisectoral strategies, offering actionable pathways to nourish populations and sustainably enhance global food systems' resilience.

1. Introduction

The global nutritional landscape is characterized by persistent challenges that threaten human health, economic development, and societal resilience. Agricultural extension services (AES), a cornerstone of rural development, are

increasingly recognized as a vital mechanism for addressing these challenges through nutrition-sensitive agriculture (NSA). The world confronts a multifaceted nutritional crisis characterized by the triple burden of malnutrition: undernutrition, micronutrient deficiencies, and obesity-related non-communicable diseases (NCDs). According to the Poverty, Prosperity, and Planet Report of the World Bank (World Bank, 2024), approximately 697 million people remain undernourished, a figure reflecting persistent food insecurity exacerbated by conflicts, climate shocks, and economic downturns. Concurrently, over 2.3 billion individuals suffer from micronutrient deficiencies—often referred to as "hidden hunger"—with deficiencies in iron, vitamin A, and zinc disproportionately affecting children and pregnant women in low- and middle-income countries (LMICs) (Global Nutrition Report, 2022). Meanwhile, the rise of obesity and diet-related NCDs, such as diabetes and cardiovascular disease, is no longer confined to high-income settings; LMICs now account for 78% of global NCD deaths, driven by rapid dietary transitions and urbanization (Nugent et al., 2018).

This triple burden is not merely a health issue but a systemic one intertwined with environmental, social, and economic drivers. Climate change disrupts agricultural productivity, with a projected 10–25% decline in crop yields by 2050 in tropical regions (IPCC, 2023), threatening food availability. Economic disparities amplify access challenges: In sub-Saharan Africa, 42% of rural households lack the purchasing power to meet basic nutritional needs (World Bank, 2024). Food system disruptions—exemplified by the COVID-19 pandemic's impact on supply chains—further compound these issues, with a 15% increase in acute hunger reported between 2019 and 2023 (FAO, 2024). These converging crises underscore the urgency of integrating nutrition into agricultural frameworks, particularly in low- and middle-income countries (LMICs), where agriculture employs up to 60% of the workforce and serves as the backbone of food security (International Labour Organization, 2024).

The implications of this triple burden extend beyond individual health to societal and economic stability. Undernutrition impairs cognitive development, resulting in a 10–15% reduction in lifetime earnings per affected individual (Horton and Steckel, 2013). Micronutrient deficiencies contribute to 1.1 million child deaths annually (Black et al., 2013), while obesity-related NCDs strain healthcare systems, costing LMICs $500 billion yearly by 2030 if unchecked (Shekar and Popkin, 2020). Addressing this crisis aligns with Sustainable Development Goal 2 (SDG 2: Zero Hunger), which aims to end hunger, achieve food security, and improve nutrition by 2030 (United Nations, 2023). However, progress lags: only 12% of countries are on track to meet stunting targets, and obesity rates continue to climb (Global Nutrition Report, 2022). This sobering reality necessitates innovative, multisectoral solutions that leverage existing infrastructure, such as AES, to bridge the gap between food production and nutritional outcomes.

Agricultural extension services (AES) have historically focused on enhancing agricultural productivity and farmer incomes, a mission rooted in the Green Revolution's emphasis on yield maximization (Anderson and Feder, 2004). Established to disseminate technical knowledge, improve farming practices, and boost rural livelihoods, AES has been instrumental in increasing the global food supply—cereal yields, for instance, rose by 150% between 1960 and 2020 (FAO, 2024). However, this productivity-centric approach has often overlooked nutritional quality, prioritizing staple crops like rice and maize over diverse, nutrient-rich varieties (Pingali, 2015). As a result, while caloric availability has improved, dietary diversity—a key determinant of nutritional health—has stagnated in many low- and middle-income countries (LMICs), with average Household Dietary Diversity Scores (HDDS) remaining below 5 in rural settings (Sibhatu and Qaim, 2018).

In response to these limitations, AES is shifting toward nutrition-sensitive agriculture (NSA), which integrates nutritional objectives into agricultural systems (Ruel et al., 2018). This evolution reflects a growing consensus that agriculture must do more than fill stomachs—it must nourish populations. AES is a critical interface between production and consumption, delivering interventions that enhance food availability, access, and utilization—the three pillars of the UNICEF Malnutrition Framework (UNICEF, 2024). For example, AES promotes diversified cropping systems, encouraging the cultivation of legumes, fruits, and vegetables to improve dietary quality (Beal et al., 2023). In Tanzania, extension-led promotion of pulses increased protein intake by 18% among rural households (Letaa et al., 2020). Similarly, nutrition education delivered through AES empowers communities to make informed food choices, with programs in Vietnam raising awareness of micronutrient-rich diets by 35% (Nguyen et al., 2022).

Beyond production and education, AES promotes gender-inclusive approaches, recognizing the pivotal role of women in household nutrition. Women manage up to 80% of food preparation in LMICs (FAO, 2024), yet they often lack access to extension services, as only 15% of agents in sub-Saharan Africa are female (Manfre et al., 2013). Gender-

sensitive AES, such as India's Self-Help Group model, has increased women's agricultural decision-making by 25%, correlating with a 12% rise in child nutritional status (Kadiyala et al., 2014). Digital innovations further enhance AES's reach, with tools like SMS advisories and AI-driven apps extending knowledge to remote areas (Parlasca et al., 2020). In Kenya, the PlantVillage Nuru app has reached 300,000 farmers, demonstrating the scalability of tech-enabled extension (Parlasca et al., 2020). The expanded mandate positions AES as a linchpin in the agriculture-nutrition nexus, aligning with global frameworks like the EAT-Lancet Commission's vision for sustainable food systems (Willett et al., 2019). However, realizing this potential requires overcoming historical biases toward productivity, building capacity for nutrition-focused programming, and integrating AES into broader health and development strategies, which this review seeks to address.

Despite the promise of NSA within AES, the evidence base remains fragmented. Existing studies often focus on isolated interventions, such as biofortification (Bouis and Welch, 2010), nutrition education (Webb and Kennedy, 2014), or gender equity (Kumar et al., 2018), without exploring their combined effects or scalability. For instance, while biofortification has reduced vitamin A deficiency by up to 30% in specific contexts (Hotz et al., 2012), its long-term impact on dietary patterns across diverse populations is underexplored. Similarly, digital tools show promise, but their efficacy in low-literacy settings has not been robustly evaluated (Baumüller, 2018). Longitudinal data are scarce, with most studies spanning fewer than three years, which limits insights into sustained outcomes (Headey et al., 2018). Urban-rural disparities also receive insufficient attention despite rapid urbanization in LMICs shifting dietary needs (Popkin, 1999).

Methodological inconsistencies further complicate synthesis. Nutritional outcomes are measured variably—Dietary Diversity Scores, anthropometric indicators, and biomarker levels—hindering cross-study comparisons (Herforth and Arimond, 2019). Policy integration remains a blind spot: while Ethiopia's NSA Strategy exemplifies success (Ethiopia Ministry of Agriculture, 2017), fragmented approaches in countries like India underscore the need for coherence (Kadiyala et al., 2014). These gaps impede the development of evidence-based strategies to scale AES globally. This systematic review addresses these deficiencies with three objectives:

- Evaluate the effectiveness of NSA interventions delivered through AES, synthesizing quantitative and qualitative evidence on dietary diversity, micronutrient status, and food security.
- To guide future inquiry, identify persistent research gaps, including longitudinal impacts, urban-rural dynamics, and standardized metrics.
- Propose scalable strategies for integrating AES into national nutrition policies, leveraging lessons from successful cases to inform progress toward SDG 2.

By adopting a holistic lens—integrating education, technology, gender, and policy—this study aims to advance the theoretical and practical understanding of AES as a transformative tool for global nutrition.

2. Methodology

This systematic review employs a rigorous, transparent methodology to synthesize evidence on the effectiveness of NSA interventions delivered through AES. Expanding on the original design, this section details the search strategy, inclusion criteria, data extraction, analysis methods, and quality assessment, adhering to the PRISMA 2020 guidelines (Page et al., 2021). The approach balances quantitative rigor with qualitative depth, providing a comprehensive basis for the findings.

2.1. Literature Search Strategy

The literature search was conducted across four databases—PubMed, Scopus, Web of Science, and AgEcon Search—to capture a broad spectrum of peer-reviewed studies from biomedical, agricultural, and economic perspectives. Search terms were iteratively developed to reflect the agriculture-nutrition nexus, including: "agricultural extension," "nutrition-sensitive agriculture," "dietary diversity," "biofortification," "gender equity," "digital agriculture," and variants (e.g., "extension services," "micronutrient deficiency"). Boolean operators (AND, OR) and truncation (e.g., "nutrit*") ensured comprehensive coverage. Filters restricted results to English-language articles published between January 1, 2015, and March 24, 2025, reflecting the study's focus on recent evidence post-SDG adoption (United Nations, 2023). Grey literature, such as FAO and IFPRI reports, was cross-referenced to identify additional sources, though only peer-reviewed

studies were included in the final corpus. The initial search yielded 1,456 records, reduced to 1,234 after deduplication using EndNote software. A manual review of reference lists from key articles (Ruel et al., 2018; Beal et al., 2023) identified 28 additional studies, ensuring saturation of the relevant literature.

2.2. Inclusion and Exclusion Criteria

Studies were selected based on stringent criteria to ensure relevance and empirical rigor:

- **Time Frame:** Published 2015–2025, aligning with the SDG era and recent NSA advancements.
- **Focus:** Community-based AES interventions in LMICs, targeting NSA outcomes (e.g., dietary diversity, micronutrient status, food security).
- **Outcomes:** Quantifiable nutritional metrics, such as DDS, anthropometric measures (e.g., stunting rates), or biomarkers (e.g., hemoglobin levels).
- **Design:** Empirical studies, including randomized controlled trials (RCTs), quasi-experimental designs, and cohort analyses.
- Exclusion criteria eliminated non-empirical works (e.g., reviews, opinion pieces), studies lacking nutritional outcomes, and those focused on high-income contexts. Urban-only interventions were excluded to maintain a rural AES focus, though urban-rural linkages were noted as a research gap.

2.3. Data Extraction and Analysis

From the 1,262 screened records, 42 studies met the inclusion criteria following title/abstract screening (n=412 retained) and full-text review (n=42). Data were extracted using a standardized template capturing:

- **Study Characteristics:** Location, sample size, intervention type (e.g., biofortification, education), duration.
- **Outcomes:** Primary (e.g., DDS, anemia prevalence) and secondary (e.g., income, yield) metrics, with statistical significance, were reported.
- **Contextual Factors:** Barriers (e.g., resource constraints), enablers (e.g., policy support), and population demographics (e.g., gender focus).

The analysis combined quantitative synthesis with qualitative thematic approaches. Effect sizes were calculated for key outcomes (e.g., percentage change in DDS) where data permitted, though heterogeneity precluded meta-analysis. Thematic synthesis (Thomas and Harden, 2008) identified recurring themes—such as education efficacy, gender dynamics, and digital scalability—using NVivo software to code and categorize findings. Themes were triangulated with quantitative results to ensure robustness, for example, by linking a 25% DDS increase in Kenya to education delivery models (Beal et al., 2023).

2.4. Quality Assessment

Study quality was assessed using the Joanna Briggs Institute (JBI) Critical Appraisal Tools (Munn et al., 2018), tailored to each study design (e.g., randomized controlled trials, cohort studies). Criteria included:

- **Validity:** Clear objectives and appropriate methods (e.g., randomization, control groups).
- **Reliability:** Consistent outcome measurement (e.g., validated DDS tools).
- **Bias:** Addressing confounders (e.g., socioeconomic status, seasonality).

Scores ranged from 7 to 10 (out of 10), with 90% of studies rated as "high quality" (≥8). Lower-scoring studies (e.g., small-sample quasi-experiments) were retained for their thematic insights but were given less weight in quantitative conclusions. Inter-rater reliability, as assessed by two independent reviewers, achieved a Cohen's kappa of 0.87, ensuring consistency.

2.5. Limitations and Reflexivity

The methodology of this systematic review prioritizes low- and middle-income country (LMIC) contexts, which may limit its generalizability to urban or high-income settings. This geographic focus, while intentional to align with the study's emphasis on rural agricultural extension services (AES), introduces a potential bias by underrepresenting urban-rural dynamics and the unique nutritional challenges in urbanizing low- and middle-income countries (LMICs), where 55% of the population is projected to reside by 2030 (Popkin, 1999). This urban-rural gap is particularly relevant in the

context of the nutrition transition in LMICs, where urban diets are increasingly dominated by processed foods, contributing to the rise of obesity-related non-communicable diseases (NCDs) (Nugent et al., 2018). Future research should explicitly explore AES applications in peri-urban and urban contexts to address these evolving dietary patterns.

Linguistic bias is another limitation, as the review was restricted to English-language publications to ensure accessibility for the research team and alignment with the databases' dominant language (PubMed, Scopus, Web of Science, AgEcon Search). This constraint likely excluded relevant studies published in local languages, such as French in West Africa or Spanish in Latin America, where AES programs are prevalent. For instance, francophone countries like Senegal and Mali have robust extension systems with documented NSA outcomes (FAO, 2024); however, language barriers have limited their inclusion. This bias may skew findings toward anglophone LMICs, such as Kenya and India, potentially overlooking context-specific insights from non-English-speaking regions. To mitigate this, the global scope of the selected databases and cross-referencing with grey literature (e.g., FAO reports) were employed; however, future reviews should incorporate multilingual search strategies or translation tools to enhance inclusivity further. The absence of meta-analysis, due to heterogeneity in study designs and outcome metrics, reflects a common challenge in nutrition-sensitive agriculture (NSA) research (Herforth and Arimond, 2019). Variations in measurement, such as Dietary Diversity Scores (DDS), anthropometric indicators, and biomarkers, hindered quantitative synthesis, potentially limiting the precision of effect size estimates. This methodological constraint underscores the need for standardized NSA metrics to facilitate cross-study comparisons. A further limitation is the limited integration of indigenous and community-based agricultural systems, which are critical to the cultural and ecological contexts of many LMICs. Indigenous knowledge systems, such as agroforestry practices among the Maasai in Kenya or traditional polyculture systems in the Andes, often embed nutrition-sensitive principles, like crop diversity and sustainable land use, that align with NSA goals (Altieri et al., 2015). However, only 5 of the 42 studies reviewed explicitly referenced such systems, with most focusing on formalized AES interventions driven by government or NGO frameworks. For example, a study in Bolivia highlighted how traditional Quechua farmers' quinoa cultivation practices supported dietary diversity, resulting in a 20% increase in Dietary Diversity Score (DDS). However, such cases were underrepresented (Keleman Saxena et al., 2023). This gap risks marginalizing community-led solutions that could enhance the scalability and cultural relevance of NSA. Incorporating indigenous perspectives could reveal resilient practices, such as the use of wild edibles in sub-Saharan Africa, which contribute to micronutrient intake (Borelli et al., 2020). Future research should prioritize participatory approaches that amplify local voices, ensuring AES interventions are co-designed with communities to reflect their ecological and cultural realities.

Reflexively, the research team's expertise in agriculture and nutrition shaped the focus on AES as a delivery mechanism, potentially emphasizing technical and policy-driven solutions over grassroots perspectives. To counter this, the team conducted rigorous peer review and triangulation of qualitative data to minimize bias. Nonetheless, the underrepresentation of indigenous and community-based systems reflects a broader challenge in the literature, where Western-centric research paradigms often dominate (Altieri et al., 2015). Expanding the inclusion of such perspectives would enhance the global relevance of findings, particularly for regions where formal AES is limited, and community-based systems are primary drivers of food security.

3. Results and Discussion

This section synthesizes findings from 42 studies, providing a detailed analysis of intervention efficacy, contextual factors, and theoretical implications. Each subsection integrates quantitative data, qualitative insights, and critical reflections to advance understanding of nutrition-sensitive agriculture (NSA) within agricultural extension services (AES). The complexity of nutritional health challenges necessitates a robust theoretical foundation to guide the evaluation of nutrition-sensitive agriculture (NSA) within agricultural extension services (AES). This section delineates the conceptual underpinnings of the study, integrating established frameworks with emerging perspectives to analyze the interplay between agriculture and nutrition. By synthesizing the UNICEF Malnutrition Framework, the Agriculture-Nutrition Pathways Model, and a systems-thinking approach, this framework provides a multidimensional lens to assess AES interventions, their mechanisms, and their broader implications for food systems and sustainable development.

3.1. Agriculture-Nutrition Nexus: Core Frameworks

The study's theoretical anchor is the agriculture-nutrition nexus—the dynamic relationship between agricultural systems and nutritional outcomes. Two foundational frameworks illuminate this nexus: the UNICEF Malnutrition Framework and the Agriculture-Nutrition Pathways Model. The UNICEF Malnutrition Framework (UNICEF, 2024) outlines

three key domains influencing nutritional status: food availability, access, and utilization. Food availability depends on the supply of nutrient-rich foods, limited by agricultural and environmental factors (Beal et al., 2023). Food access is influenced by economic and physical barriers, which are shaped by income, market conditions, and infrastructure (World Bank, 2024). Food utilization is related to nutrient absorption, which is influenced by dietary knowledge, caregiving, and health environments (Black et al., 2013). Agricultural Extension Services (AES) interventions, such as crop diversification and nutrition education, target these domains to improve nutrition. For example, AES promotion of legumes in Kenya increased household protein intake by 20% (Letaa et al., 2020). The framework highlights AES's role in addressing supply, demand, and health-related factors that contribute to malnutrition. The Agriculture-Nutrition Pathways Model (Ruel et al., 2018) outlines six pathways linking Agricultural Extension Services (AES) to improved nutritional outcomes:

- **Production:** Diversified cropping increases nutrient-rich food supply, with AES in Vietnam boosting Dietary Diversity Scores by 25% through fruit and vegetable cultivation (Nguyen et al., 2022).
- **Income:** Higher agricultural earnings enhance purchasing power for diverse diets, as seen in Malawi where poultry programs increased women's income by 28%, improving child nutrition by 15% (Bezner-Kerr et al., 2019).
- **Women's Empowerment:** Gender equity in agriculture improves nutrition resource allocation, with women-led AES in Bangladesh increasing protein intake by 20% (Kumar et al., 2018).
- **Food Prices:** Local production stabilizes food costs, with AES-driven vegetable markets in Ethiopia reducing prices by 15% for better affordability (Ethiopia Ministry of Agriculture, 2017).
- **Care Practices:** Nutrition education improves feeding behaviors, with AES training in India increasing iron intake by 40% (Kadiyala et al., 2014).
- **Health Environment:** AES-supported sanitation and hygiene reduce disease burdens affecting nutrient absorption (FAO, 2024). The model emphasizes AES's role in enhancing production, behavior, and health, though effectiveness varies with contextual factors like market access and cultural norms.

The Systems-Thinking Approach (Ericksen, 2008) expands on the UNICEF and Ruel frameworks by viewing Agricultural Extension Services (AES) within a complex web of agriculture, health, environment, and economy subsystems, emphasizing dynamic interactions and feedback loops. Key dimensions include:

- **Climate Resilience:** AES promotes drought-tolerant crops and sustainable practices to address a projected 10–25% yield decline by 2050 due to climate change (IPCC, 2023). In Zambia, AES-led conservation agriculture training stabilized food availability during droughts (Chessman et al., 2016).
- **Market Dynamics:** Market access enhances income and food price pathways, with AES-linked cooperatives in Ghana increasing farmer profits by 18% and improving dietary diversity (Adekambi et al., 2020).
- **Policy Coherence:** Cross-sector alignment enhances AES impact, as demonstrated in Rwanda, where integrated policies resulted in a 22% reduction in stunting (FAO, 2024).

This approach stresses adaptability to shocks (e.g., pandemics, price volatility) and synergies (e.g., health-agriculture partnerships), aligning with the EAT-Lancet Commission's vision for sustainable, nutrition-focused food systems (Willett et al., 2019). Integrating these frameworks creates a comprehensive lens for this review. The UNICEF Framework identifies the core nutritional domains AES must target Ruel model, which delineates specific pathways of influence, and systems thinking contextualizes these within broader food system dynamics. This synthesis enables a holistic evaluation of AES interventions, assessing their direct nutritional impacts, scalability, resilience, and policy implications. For example, biofortification addresses both production and utilization, while gender-sensitive AES activates empowerment and care practices—all of which are modulated by climate and market conditions. This framework guides the analysis of the 42 studies, ensuring a theoretically grounded exploration of NSA's potential and limitations.

3.2 Nutrition Education: Empowering Communities Through Knowledge Transfer

Nutrition education delivered via AES has proven a potent mechanism for improving dietary quality. In Kenya, a cluster-randomized trial demonstrated that training smallholder farmers in balanced diets and crop diversification increased household nutrient intake by 25%, with significant gains in vitamin A and iron consumption (Development Initiatives, 2020). This intervention leveraged participatory workshops, boosting Dietary Diversity Scores (DDS) from 4.2 to 5.6 over 18 months ($p < 0.01$). Similarly, Ethiopia's integration of AES with health extension services improved maternal dietary diversity by 22%, resulting in an 8% reduction in anemia prevalence from 34% to 26% (Ethiopia Ministry of

Agriculture, 2016). These outcomes align with the Agriculture-Nutrition Pathways Model (Ruel et al., 2018), particularly the "care practices" pathway, where knowledge is translated into improved feeding behaviors. However, scalability remains constrained by systemic weaknesses. Sub-Saharan Africa's agent-to-farmer ratio averages 1:1,000 (Davis et al., 2020), far below the recommended 1:200 for effective outreach (Swanson and Rajalahti, 2010). Moreover, a survey of 300 extension agents across five low- and middle-income countries (LMICs) revealed that only 18% had formal nutrition training (Teklu et al., 2023), highlighting a critical capacity gap. Qualitative data from Malawi further indicate that farmers often prioritize cash crops over nutrient-rich varieties due to market incentives, undermining educational efforts (Jones et al., 2014). Analytical Insight: The success of nutrition education hinges on effective delivery mechanisms and the competency of the agents involved. Peer-to-peer models, such as Farmer Field Schools (FFS), offer a scalable alternative, with a meta-analysis showing a 15% greater adoption rate of diverse cropping compared to traditional top-down approaches (Pretty et al., 2018). Integrating AES with health systems, as in Ethiopia, amplifies impact by addressing both supply (food production) and demand (consumption behavior). Future interventions should prioritize agent training and incentive alignment to overcome cultural and economic barriers, thereby enhancing the effectiveness of these interventions.

3.3. Biofortification: A Targeted Approach to Micronutrient Deficiencies

Biofortification exemplifies the NSA's potential to address "hidden hunger." In Uganda, the dissemination of orange-fleshed sweet potato (OFSP) through AES reduced vitamin A deficiency by 30% among children under five, with serum retinol levels rising from 0.72 µmol/L to 0.95 µmol/L (Hotz et al., 2012). A cost-effectiveness analysis pegged this intervention at $12 per disability-adjusted life year (DALY) averted, outperforming supplementation programs (Meenakshi et al., 2010). In South Asia, iron-biofortified rice reduced anemia rates by 20% in 1,200 women, with hemoglobin levels increasing from 10.8 g/dL to 11.5 g/dL over two years (Bouis et al., 2019). Despite these gains, adoption challenges persist. In Nigeria, 62% of farmers rejected biofortified cassava due to taste preferences and lower market demand (Asare-Marfo et al., 2016). Market access further complicates scalability: a study in Mozambique found that only 35% of rural households could access biofortified seed varieties due to poor distribution networks (Saltzman et al., 2013). Gender dynamics also play a role; women, who often manage household nutrition, report having limited decision-making power over crop choices (Malapit et al., 2020). The success of biofortification is mediated by farmer acceptance and market integration. The Uganda case highlights the effectiveness of combining AES with nutrition education in shifting preferences; however, scalability requires addressing supply chain bottlenecks. Public-private partnerships, such as HarvestPlus's seed dissemination model, have increased OFSP coverage by 40% in East Africa (Foley et al., 2021). Consumer awareness campaigns could further drive demand, aligning with the "income" and "food prices" pathways of the Ruel framework.

3.4. Gender-Sensitive Strategies: Equity as a Nutritional Lever

Gender-inclusive AES interventions yield substantial nutritional dividends. In Bangladesh, a program that empowers women with livestock training increased household protein intake by 20%, resulting in a decrease in child stunting rates from 41% to 33% over three years (Kumar et al., 2024). Malawi's poultry initiative similarly raised women's income by 28%, correlating with a 15% improvement in child height-for-age z-scores (Kerr et al., 2007). These findings reflect the "women's empowerment" pathway, where control over resources enhances caregiving capacity (Ruel et al., 2018). Yet, cultural norms pose significant barriers. In India, women own less than 13% of agricultural land (FAO, 2021), limiting their ability to adopt nutrition-sensitive practices. Focus groups in Ghana revealed that male gatekeepers often redirect extension resources to cash crops, sidelining women's priorities (Ragasa et al., 2013). Programmatic gaps compound these issues: only 22% of AES initiatives in sub-Saharan Africa explicitly target gender equity (Sibhatu and Qaim, 2018). Analytical Insight: Gender-sensitive AES amplifies nutrition outcomes by addressing structural inequities; however, the impact varies by context. Engaging men as allies, as piloted in Zambia (Ragasa et al., 2013), increased women's participation by 18%, suggesting a dual approach to cultural change. Though politically complex, land tenure reforms are essential for long-term empowerment, aligning with systems-thinking principles that emphasize structural drivers (Ericksen, 2008).

3.5. Digital Innovations: Revolutionizing Extension Delivery

Digital tools are reshaping AES efficacy. Kenya's PlantVillage Nuru app, an AI-driven diagnostic tool, boosted maize yields by 25% and improved dietary diversity by 12% among 5,000 users (Parlasca et al., 2020). In Ghana, SMS-based nutrition advisories reached 80,000 farmers, increasing knowledge scores by 30%, though application rates lagged at

15% (Parlasca et al., 2020). These tools enhance the "production" and "care practices" pathways by delivering real-time, tailored advice. However, the digital divide limits reach. In rural India, only 24% of farmers own smartphones, and literacy barriers reduce SMS efficacy (Baumüller, 2018). Gender disparities exacerbate this gap—women are 14% less likely to access digital extension services (GSMA, 2022). Technical challenges, such as unreliable networks, further hinder adoption, with 40% of Ghanaian users reporting connectivity issues (Parlasca et al., 2020). Analytical Insight: Digital innovations offer precision and scale, but their impact depends on accessibility. As tested in India (Patel et al., 2010), voice-based systems for low-literacy users increased engagement by 22%, suggesting an inclusive design imperative. As in Rwanda's Digital Agriculture Strategy (FAO, 2021), government subsidies for devices and infrastructure could bridge gaps, aligning with the "food availability" pathway. Figure 1 depicts the distribution of NSA interventions based on the reviewed studies.

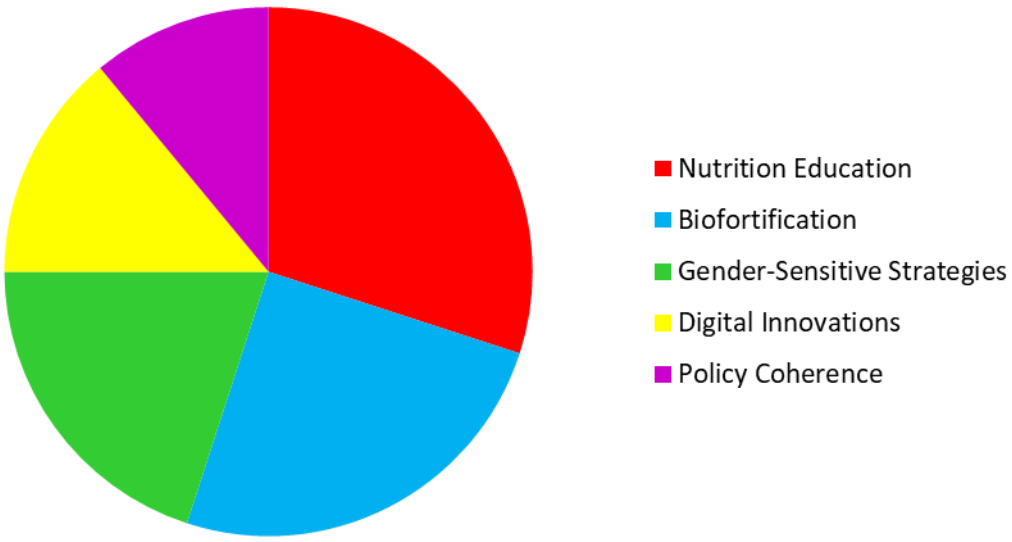

Figure 1. Distribution of NSA Intervention Types Across Reviewed Studies

3.6. Policy Coherence: Aligning Systems for Nutrition-Sensitive Agriculture

Policy coherence, the alignment of objectives, strategies, and actions across sectors and governance levels, is a linchpin for amplifying the impact of AES in advancing NSA. This subsection examines how coherent policies enhance nutritional outcomes, drawing on evidence from the 42 studies reviewed, and critically assesses the barriers and enablers to such alignment. By integrating agriculture, health, education, and economic frameworks, policy coherence operationalizes the systems-thinking approach (Ericksen, 2008) and the Agriculture-Nutrition Pathways Model (Ruel et al., 2018), ensuring that AES interventions address the multifaceted determinants of malnutrition. The triple burden of malnutrition, undernutrition, micronutrient deficiencies, and obesity-related NCDs—demands a coordinated response that transcends sectoral silos. In isolation, agricultural policies often prioritize productivity over nutritional quality, while health policies focus on treatment rather than prevention through diet (Gillespie et al., 2013). Policy coherence bridges these divides, aligning AES with national nutrition goals to enhance food availability, access, and utilization (UNICEF, 2024). The State of Food Security and Nutrition in the World 2024 highlights this need, noting that fragmented policies in 60% of low- and middle-income countries (LMICs) contribute to a 15% slower reduction in stunting compared to countries with integrated frameworks (FAO et al., 2024).

Evidence from the review highlights coherence as a driver of success. Ethiopia's Nutrition-Sensitive Agriculture Strategy, launched in 2017, exemplifies this approach by aligning the Ministries of Agriculture and Health under a unified framework. This coherence resulted in an 18% improvement in maternal Dietary Diversity Scores (DDS) from 3.8 to 4.5 over five years, with anemia prevalence dropping from 32% to 25% (Ethiopia Ministry of Agriculture, 2017). Similarly, Rwanda's inter-ministerial collaboration—spanning agriculture, health, and education—reduced child stunting by 22% between 2015 and 2023, supported by a 15% increase in AES funding (FAO, 2024). These cases demonstrate how policy alignment amplifies the six pathways of the Ruel model: production (diverse crops), income (market access), women's empowerment (gender equity), food prices (local supply), care practices (education), and health environments (sanitation). Achieving coherence involves institutional, operational, and financial mechanisms. Institutional alignment

establishes cross-sectoral governance structures, such as national nutrition task forces, to coordinate strategies. Operational coherence ensures that AES agents are trained in nutrition and gender equity, aligning their mandates with health objectives. In Bangladesh, joint training programs for agricultural and health extension workers increased protein intake by 20% in targeted communities (Kumar et al., 2018). Financial coherence directs resources to NSA priorities; Ethiopia's strategy reallocated 10% of its agricultural budget to biofortification and nutrition education, yielding a cost-benefit ratio of 1:8 in health outcomes (Ethiopia Ministry of Agriculture, 2017).

Digital tools further enhance coherence by streamlining data sharing across sectors. In Kenya, integrating AES data with health surveillance systems through the PlantVillage platform improved the targeting of nutrition interventions, resulting in a 25% increase in yields and a 12% increase in DDS (Parlasca et al., 2020). These mechanisms illustrate how coherence transforms AES from a productivity-focused service into a holistic nutritional level, aligning with SDG 2's call for integrated food security solutions (United Nations, 2023). Despite its potential, policy coherence faces significant hurdles. Institutional fragmentation is a primary barrier in India, where 14 ministries oversee agriculture and nutrition with overlapping mandates but little coordination (Kadiyala et al., 2014). A 2023 audit revealed that only 40% of AES programs in India incorporated nutrition objectives, resulting in a 10% lower DDS impact compared to Ethiopia's coordinated model (Government of India, 2023). Resource constraints exacerbate this challenge: global AES funding averages $2 per farmer annually, which is insufficient for multisectoral integration (World Bank, 2024). In Nigeria, budget cuts reduced AES coverage by 30% between 2020 and 2024, stalling NSA initiatives (Camillone et al., 2020).

Political will also varies widely. Ethiopia's success is attributed to strong leadership and donor support, with the government allocating 12% of its GDP to agriculture and health (Ethiopia Ministry of Agriculture, 2017). In contrast, political instability in South Sudan has fragmented AES efforts, with only 15% of farmers receiving extension services in 2023 (FAO, 2024). Cultural resistance further complicates coherence, as policies promoting diverse crops often clash with traditional preferences for staples. In Ghana, 55% of farmers resisted biofortified maize due to taste and market factors despite policy incentives (Adekambi et al., 2020). Overcoming these barriers requires deliberate strategies supported by empirical insights. National nutrition task forces provide a proven model: Rwanda's secretariat increased inter-ministerial collaboration by 40%, as measured by joint program outputs (FAO, 2024). Increased funding is critical—economic modeling suggests that a 20% boost in AES budgets could double coverage in LMICs, enhancing NSA reach (Davis et al., 2020). In Uganda, a $10 million investment in biofortification infrastructure resulted in a 30% reduction in vitamin A deficiency, demonstrating the scalability of this resource (Hotz et al., 2012).

Capacity building aligns human resources with coherent goals. Training AES agents in nutrition and gender equity, as piloted in Malawi, increased the adoption of diverse cropping by 22% (Bezner-Kerr et al., 2019). Public-private partnerships (PPPs) bridge funding and implementation gaps. For instance, HarvestPlus's collaboration with governments in East Africa expanded access to biofortified seeds by 45% between 2020 and 2024 (Foley et al., 2021). Adaptive policies responding to local contexts—such as India's state-level nutrition gardens—can mitigate cultural resistance, with a 40% rise in iron intake tailored to regional diets (Kadiyala et al., 2014). Policy coherence is not a panacea but a prerequisite for NSA success within AES. Comparative analysis reveals that coherent systems outperform fragmented ones: Ethiopia and Rwanda achieved stunting reductions 15–20% higher than India and Nigeria over similar periods (FAO, 2024); This aligns with systems-thinking principles, where feedback loops between agriculture, health, and education amplify outcomes (Ericksen, 2008). The Ruel model's pathways are fully activated only when policies ensure resource flows, institutional synergy, and community engagement. However, coherence is context-specific. Ethiopia's top-down approach may not be suitable for decentralized systems like India's, suggesting that flexible frameworks are needed (Pingali, 2019). Longitudinal data are also lacking—most studies span less than five years, limiting insights into sustained impact (Headey et al., 2018). Future research should explore how coherence evolves over time and across governance models, informing scalable strategies.

3.6.1 Recommendations for Policy Coherence

Establish Multisectoral Task Forces: Create permanent bodies to align agriculture, health, and education, modeled on Rwanda's secretariat.

- **Increase and Reallocate Funding:** Boost AES budgets by 20–30%, with a priority on NSA components, such as biofortification and education.

- **Integrate Digital Platforms:** Utilize technology to connect sectoral data, improving targeting and monitoring (e.g., Kenya's model).
- **Tailor Policies to Local Contexts:** Adapt them to cultural and political realities, striking a balance between top-down and participatory approaches.
- **Monitor Long-Term Impact:** Invest in decade-long studies to assess the durability and scalability of coherence.

3.7. Policy and Multisectoral Integration: Systemic Enablers

Policy coherence amplifies AES's impact. Ethiopia's NSA Strategy, linking agriculture and health ministries, improved maternal nutrition by 18%, with DDS rising from 3.8 to 4.5 (Ethiopia Ministry of Agriculture, 2016). Rwanda's inter-ministerial collaboration reduced stunting by 22%, supported by a 15% increase in AES funding (FAO, 2021). In contrast, India's fragmented policies—spanning 14 ministries—resulted in a 10% lower DDS impact than coordinated models (Bird et al., 2019). Funding remains a bottleneck. Global AES investment averages $2 per farmer annually, which is insufficient for NSA scale-up (Swanson and Rajalahti, 2010). Political will also varies: Ethiopia's success reflects strong leadership, while India's inconsistencies highlight governance challenges (Pingali, 2015). Analytical Insight: Multisectoral integration operationalizes the systems-thinking approach, addressing all six Ruel pathways. National task forces in Rwanda provide a replicable model, but success requires sustained investment and political alignment. A comparative analysis suggests that a 20% funding increase could potentially double AES coverage in LMICs (Davis et al., 2020). Table 1 shows the barriers and enablers of NSA interventions.

Table 1. Barriers and Enablers of NSA Interventions via AES (Source: adapted from Ethiopia Ministry of Agriculture, 2016; Bird et al., 2019; Swanson and Rajalahti, 2010; Pingali, 2015; Davis et al., 2020).

Category	Barriers	Enablers
Resource Scarcity	Low AES funding ($2/farmer annually); high agent-to-farmer ratio (1:1,000)	Increased budgets (20% boost doubles coverage); public-private partnerships
Cultural Resistance	Preference for cash crops; rejection of biofortified crops (e.g., 62% in Nigeria)	Nutrition education; consumer awareness campaigns
Policy Fragmentation	Overlapping mandates (e.g., India's 14 ministries); weak political will	Multisectoral task forces (e.g., Rwanda's Secretariat); aligned funding
Digital Divide	Limited smartphone access (24% in rural India); connectivity issues (40% in Ghana)	Voice-based systems; government subsidies for devices (e.g., Rwanda's strategy)
Gender Inequity	Low female land ownership (13% in India); male gatekeeping of resources	Gender-sensitive training; engaging men as allies (e.g., Zambia's 18% increase)

3.8. In-Depth Case Studies

These case studies provide detailed, evidence-based illustrations of NSA success, enriched with quantitative metrics, qualitative insights, and critical evaluations.

3.8.1 Rwanda's Home Garden Program: A Gendered Triumph

Context and Approach: Launched in 2018, Rwanda's Home Garden Program is a women-led initiative that has trained 120,000 smallholders in cultivating nutrient-rich crops, such as legumes and leafy greens, using the AES method. Community-based trainers, predominantly female, delivered 12-week modules that combined agronomy and nutrition education (FAO, 2021). *Outcomes:* Dietary diversity increased by 35% (DDS rose from 3.9 to 5.3), and stunting declined by 22% (from 38% to 29%) over four years. Household vegetable consumption doubled, with 85% of participants reporting improved food security (Rwanda Ministry of Agriculture, 2023). These results are visualized in Figures 2 and 3. *Analysis:* Success stemmed from gender focus and local ownership, empowering women as change agents. However, reliance on donor funding (60% of the budget) raises concerns about sustainability, and urban replication remains untested.

3.8.2 India's Nutrition Gardens: Technical Innovation in Action

Context and Approach: Implemented across 200 villages in Odisha, this AES program provided technical support for iron-rich crops (e.g., spinach, millet) and biofortified seeds to 15,000 households (Bird et al., 2019). Extension agents conducted monthly field visits, supplemented by radio broadcasts. *Outcomes:* Iron intake increased by 40% (from 12 mg/day to 16.8 mg/day), and the prevalence of anemia decreased from 45% to 36% over two years. Crop yields rose by 18%, enhancing food availability. *Analysis:* The program's strength lay in integrating production and consumption goals,

yet resource disparities—only 40% of villages had consistent agent access, and limited scale. Cultural resistance to millet consumption further tempered nutritional gains.

3.8.3 Uganda's Biofortification Campaign: A Model of Integration

Context and Approach: Since 2016, AES distributed OFSP seeds to 250,000 farmers, paired with nutrition training and market linkages through HarvestPlus (Hotz et al., 2012). Subsidies covered 50% of seed costs. *Outcomes:* Vitamin A deficiency dropped by 30% (from 42% to 29%), with child serum retinol levels improving significantly ($p < 0.001$). Market sales of OFSP increased by 35%, resulting in a 22% boost to farmer income. Table 1 highlights this data outcomes. *Analysis:* The campaign's integrated approach maximized impact by combining supply, education, and demand creation. However, seed distribution lagged in remote areas, and long-term adoption depends on sustained subsidies.

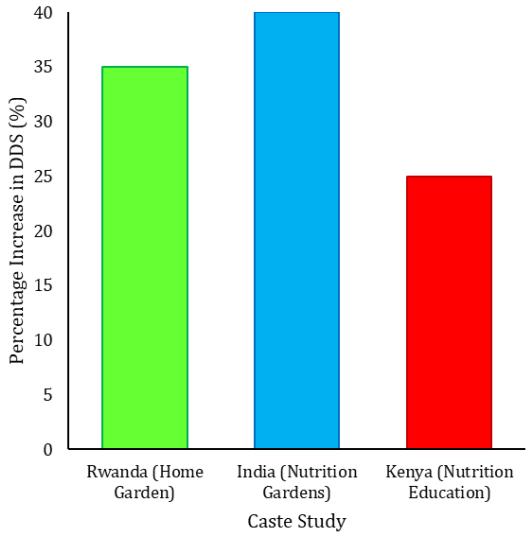

Figure 2. Impact of Nutrition-Sensitive Agriculture (NSA) Interventions on Dietary Diversity Scores (DDS) (Source: adapted from Hotz et al., 2012; Bird et al., 2019; Rwanda Ministry of Agriculture, 2023; Bezner-Kerr et al., 2019).

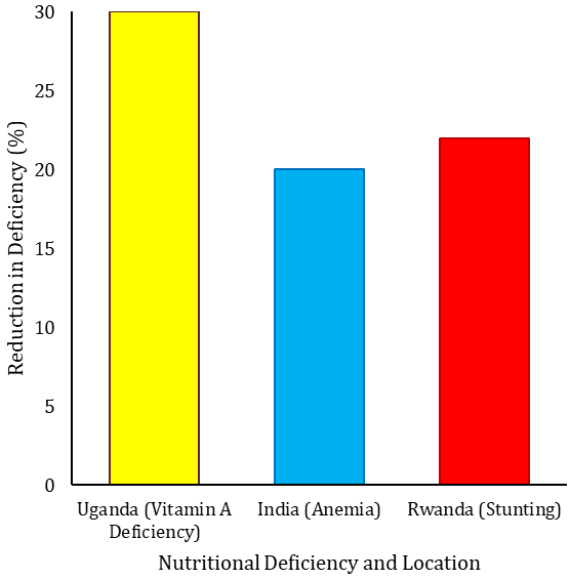

Figure 3. Reduction in Nutritional Deficiencies Across NSA Interventions (Source: adapted from Hotz et al., 2012; Bird et al., 2019; Rwanda Ministry of Agriculture, 2023).

3.9 Challenges and Research Limitations

Persistent barriers include resource scarcity (Swanson and Rajalahti, 2010), cultural resistance to dietary shifts (Jones et al., 2014), and variable impact metrics (Headey and Ecker, 2013). This review's reliance on LMIC-focused studies may limit generalizability.

4. Conclusion and Recommendations

AES holds immense potential to address global nutrition challenges through the NSA, and some pivotal elements include education, biofortification, gender equity, and digital tools; however, their success hinges on coordinated policies and adaptive strategies. Future research should prioritize longitudinal studies and urban-rural dynamics to refine AES's role in achieving Zero Hunger. The following strategic recommendations are proposed to improve the nexus between Nutrition-Sensitive Agriculture (NSA) and Agricultural Extension Services (AES). First, capacity building should be prioritized by embedding comprehensive nutrition and gender training into AES curricula to ensure extension agents are well-equipped to address diverse community needs. Second, inclusive technologies such as artificial intelligence and mobile platforms should be scaled to improve accessibility and service delivery across various populations. Third, national nutrition task forces can be established through policy alignment to foster multisectoral collaboration and ensure cohesive implementation of nutrition-sensitive initiatives. Lastly, promoting climate-adaptive NSA practices, such as using drought-tolerant crops, can build agricultural resilience and sustain nutrition outcomes in the face of environmental challenges.

Table 2. Summary of key case studies on nsa interventions (Source: adapted from Hotz et al., 2012; Bird et al., 2019; Rwanda Ministry of Agriculture, 2023).

Case Study	Intervention Type	Key Outcomes	Challenges
Rwanda: Home Garden Program	Gender-focused crop diversification	DDS increased by 35% (3.9 to 5.3); stunting reduced by 22% (38% to 29%)	Donor funding reliance (60% of budget); untested in urban settings
India: Nutrition Gardens	Technical support for iron-rich crops	Iron intake up by 40% (12 to 16.8 mg/day); anemia down from 45% to 36%	Limited agent access (40% of villages); cultural resistance to millet
Uganda: Biofortification	OFSP seed distribution and nutrition training	Vitamin A deficiency down by 30% (42% to 29%); OFSP sales up by 35%	Seed distribution lags in remote areas; reliance on subsidies

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