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Review

Agricultural Extension for Adopting Technological Practices in Developing Countries: A Scoping Review of Barriers and Dimensions

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Abstract: This scoping review employed the PRISMA-ScR framework to dissect the complexities of technological extension in agriculture within developing nations, where varying socio-economic, cultural, and environmental facets deeply influence extension strategies. Our study aimed to identify and expand upon the existing knowledge of critical factors—both challenges and opportunities—that affect the efficacy of agricultural extension, with a focus on contextual variations. To achieve this, we conducted a comprehensive review of the relevant academic contributions from 2013 onwards. This included articles, reviews, conference proceedings, book chapters, and data papers. Our analysis focused on scrutinizing the interaction dynamics between extension personnel and farmers, the adaptation of technologies to local contexts, and the significance of cross-sector collaboration. Through bibliometric analysis, we provide a synthesis of 32 pertinent records. Our findings advocate for a paradigm shift from the traditional linear knowledge transfer to a more encompassing approach that values bidirectional communication, cultural awareness, and the active involvement of local farming communities. We argue for extension practices that are attuned to environmental dynamics, promote long-term economic sustainability, and are informed by theoretical perspectives that can refine the design of extension systems and models. Our review posits that the enhancement of sustainable agricultural technology adoption lies in a profound reform of extension systems. Such reform should focus on design and operational models that are more inclusive, adaptive, and acutely attuned to the complex realities of farmers in emerging economies. This integrative, systemic, and holistic approach proposes a framework to bolster agricultural sustainability and rural development.

Keywords: agricultural extension; developing countries; scoping review; sustainable agriculture; technological adoption

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1. Introduction

Agriculture remains the linchpin of both the economy and food security in emerging economies, where farmer families face persistent challenges hindering productivity and sustainability [1]. Market imperfections often curtail access to vital information, technology (e.g., information related to agricultural production, certifications, and quality control), managerial skills, and technical expertise, which are indispensable for implementing conventional and sustainable agricultural practices. These imperfections include, but are not limited to, limited knowledge of optimal cultivation techniques, complex technologies, quality of seeds, technical requirements for production, a lack of supervisory mechanisms for labor and technology adoption, the unavailability of specialized inputs, and the high costs of sophisticated equipment [2].

Salehi et al. (2021) [3] highlight a spectrum of critical factors contributing to low productivity, such as inadequate crop design and planning, suboptimal environmental conditions, the use of ineffective practices, and the low technification of essential processes like irrigation and drainage. These factors are compounded by a lack of new technology adoption, the absence of improved cultivars, deficiencies in fertilization, and scarce agricultural mechanization [4]. Wordofa (2019) [5] points out that these issues are further exacerbated by the limited training of farmers and decision-makers, resulting in limited human resource development and a diminished capacity to capitalize on technological advancements to increase agricultural profitability [6]. Additionally, several challenges arise due to pest and disease impacts on crops, necessitating higher investments in management and more stringent implementation of preventive and curative practices [7].

Despite global technological advancements aiming to elevate productivity rates, implementing such innovations has been disproportionately ineffective in certain regions, often yielding returns that fall short of crops' genetic and economic potentials [8]. Technological extension, identified as an essential driver for technological adoption as well as the enhancement of living conditions for rural agricultural families [9], necessitates an approach that is deeply embedded in the populations' needs and addresses the technical, economic, environmental, and social barriers specific to each country [2].

Successful technological extension depends on managing these determinants of low productivity [3,4,6]. It is conditioned by the ability to integrate and adapt innovations into existing practices and systems Loevinsohn et al. (2013) [10], Takahashi et al. (2020) [11], Martínez (2022) [12], and Acheampong et al. (2024) [13], emphasizing the need for extension workers to be facilitators rather than mere conveyors of technology [14].

Extension services were introduced and mainly sponsored by public administrations during the 'Green Revolution' in the 1970s and early 1980s to increase productivity [15]. Traditional extension models followed a top-down linear approach, wherein technologies developed by technical experts (research and academic institutes) were transferred to farmers with little to no participatory engagement [16,17]. Leeuwis (2005) [18], calls for a reinvention of extension strategies, encouraging the exchange of knowledge and experiences, co-design, and negotiation amongst all stakeholders, accounting for technical, structural, and contextual factors.

Swanson et al. (2010) [19] underscore the primary objective of extension as enhancing the uptake of technologies within the paradigm of sustainable agriculture development, which is also echoed by Bakar (2012) [2]. A cohesive extension system can thus significantly influence food security, poverty alleviation, rural empowerment, and environmental conservation [20,21]. Agbarevo and Machiadikwe (2013) [22], however, point out that extension systems often suffer from inefficiencies such as the dissemination of irrelevant messages [23], a deficit of credible experience among extensionists [24], and a lack of mechanisms to effectively communicate farmers' primary concerns to agricultural researchers at institutes and universities [25,26].

Furthermore, Feder et al. (2006) [27] observe that the motivational levels of poorly compensated professionals within extension systems can significantly dampen the effectiveness of these services. Moreover, Danso-Abbeam et al. (2018) [28] propose that in developing countries, there is not enough understanding of producers' interests, as it is assumed they are always interested in maximizing the productivity and profitability of their crops, which is not always the case; for example, sometimes field conditions lead some groups to aim to leave rural life and live in the city [29].

Farrington (1995) [30] observes that while there are numerous examples of successful public agricultural extension initiatives, there also exists a pattern of inefficiencies characterized by the ineffective distribution of resources, inflexibility, and an inability to respond to specific and changing institutional contexts and infrastructures [31].

Therefore, the framework of technological extension in agriculture has changed drastically in recent years [32]. The challenges outlined by various scholars underscore the necessity for a comprehensive overhaul of the agricultural extension framework, particularly considering fiscal constraints, the expanding role of the private sector, and the changing priorities of donors amidst the backdrop of globalization's impact on agriculture [33].

Extension systems have undergone extensive evaluations and reforms globally [33]. Attention has shifted towards innovative models of technological transfer that include both public and private systems and consider producers' specific needs and challenges [30]. Ali Mengal et al. (2016) [34] emphasize the importance of identifying producers' needs, articulating key actors, adapting practices to various contexts, and the complementary assets required for the successful implementation and scalability of technological advancements in agriculture [35,36].

This scoping review aims to assess the challenges and opportunities in extension processes that foster the effective and widespread adoption of technology for sustainable agricultural development in developing countries. It synthesizes and integrates findings from previous research, examining how technological extension, when designed and implemented with consideration of the socioeconomic and cultural conditions specific to each producer and region, can overcome the critical factors in the agricultural sector [37].

The methodology of this review follows a rigorous and systematic approach called PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses—Extension for Scoping Reviews), which allows a coherent and transparent synthesis of the existing literature [38]. Through this analysis, it was possible to set the stage for identifying successful practices and formulating recommendations for the design of more impactful extension interventions.

By thoroughly analyzing these multifaceted dimensions, this research contributes significantly to the literature on agricultural extension by providing a comprehensive and up-to-date understanding of the multiple factors influencing agricultural extension processes. It outlines a theoretical framework that can guide future strategic endeavors and policies within the agricultural sector. It aims to lay down a solid foundation for executing technological extension programs attuned to the needs and realities of farmers, thus fostering sustainable agricultural development.

2. Methods and Protocol

In this review, we employed the PRISMA-ScR approach as conceptualized by Arksey and O'Malley (2005) [39], later refined by Levac et al. (2010) [40], and the Joanna Briggs Institute [41], and finally parameterized by Tricco et al. (2018) [38]. The PRISMA-ScR framework is particularly apt for our study as it enables a comprehensive inquiry into the widely indexed literature and diverse information sources. This includes academic articles, systematic reviews, conference proceedings, book chapters, data papers, and even editorial content, acknowledging the multi-methodological nature of existing research [42]. Given the broad range of information collected, formal meta-analytic techniques were not feasible. Instead, the PRISMA-ScR facilitated an analysis focused on the range of content presented, often culminating in a numerical accounting of sources related to specific topics or recommendations.

According to Munn et al. (2018) [43], scoping reviews can help map out a particular field of study by identifying the available evidence, elucidating definitions, dissecting research methodologies, pinpointing characteristic features, and highlighting areas lacking knowledge. The ScR methodology mandates that the objectives of the review must be meticulously aligned with its intended purpose, ensuring a structured and targeted approach [38,44].

We selected the scoping review method for this work due to the significant diversity of resources related to agricultural extension services. Many of these are disseminated through non-peer-reviewed or less academically traditional mediums, providing a richer, more nuanced understanding of the subject matter.

2.1. Guiding Questions (GQ) for the Scoping Review

The framing of Guiding Questions (GQs) is a critical step in conducting a ScR as they set the boundaries of inquiry, dictate inclusion and exclusion criteria, and shape the subsequent analysis. For this review of critical factors affecting technological extension strategies in agriculture within developing countries, the GQs were crafted to elicit focused insights:

- GQ1: What principles underpin the technological extension strategies employed in the agricultural sector of developing countries?
- GQ2: How do cultural, economic, and political variances influence the implementation and assimilation of agricultural technologies?
- GQ3: What are the critical factors that influence the efficacy of technological extension strategies in the agricultural sector of developing countries?
- GQ4: How do extension services impact the adoption of technologies aimed at sustainable agricultural practices?

2.2. Strategies for Document Selection

To construct a foundation for this scoping review, specific criteria were meticulously crafted to delineate which materials would be included for analysis.

The review encompassed the following:

- Empirical and theoretical studies probing into the critical factors of implementing technological extension strategies within the agricultural sector.
- Scholarly inquiries analyzing the impact of technological extension strategies on enhancing agricultural productivity and sustainability.
- Literature with an explicit focus on the metrics of efficiency of agricultural extension practices.
- Articles delineating the barriers and facilitators intrinsic to the adoption of agricultural technologies.
- Publications investigating the impact of education and formal training on adopting agricultural technology.
- Analytical evaluations consider the effect of government policies and regulatory frameworks on the practice of technological extension.
- In-depth case studies and program evaluations about applying technological extension strategies in developing countries.
- Conversely, this study excluded the following:
- Studies concentrated exclusively on the agricultural practices of developed countries without extrapolative relevance.
- Literature not focusing specifically on agricultural practices, technologies, or innovations.
- Publications needing more empirical data or failing to expose the critical factors under scrutiny adequately.

2.3. Method for Scoping Review and Analysis

Following the parameters of the PRISMA-ScR approach [38], a meticulous two-stage document retrieval process was initiated. Sources from databases such as Scopus, Semantic Scholar, and Web of Science were scoured. The initial bibliometric analysis comprised the first phase of discovery, followed by a second phase where keywords that surfaced as recurrent and interconnected from the initial stage were incorporated.

As this is an ScR, the initial list included documents that reported original research, were written in English, and were accompanied by an abstract or executive summary. The literature search was conducted between December 2023 and February 2024. The flowchart of the search strategy and selection process is shown in Figure 1.

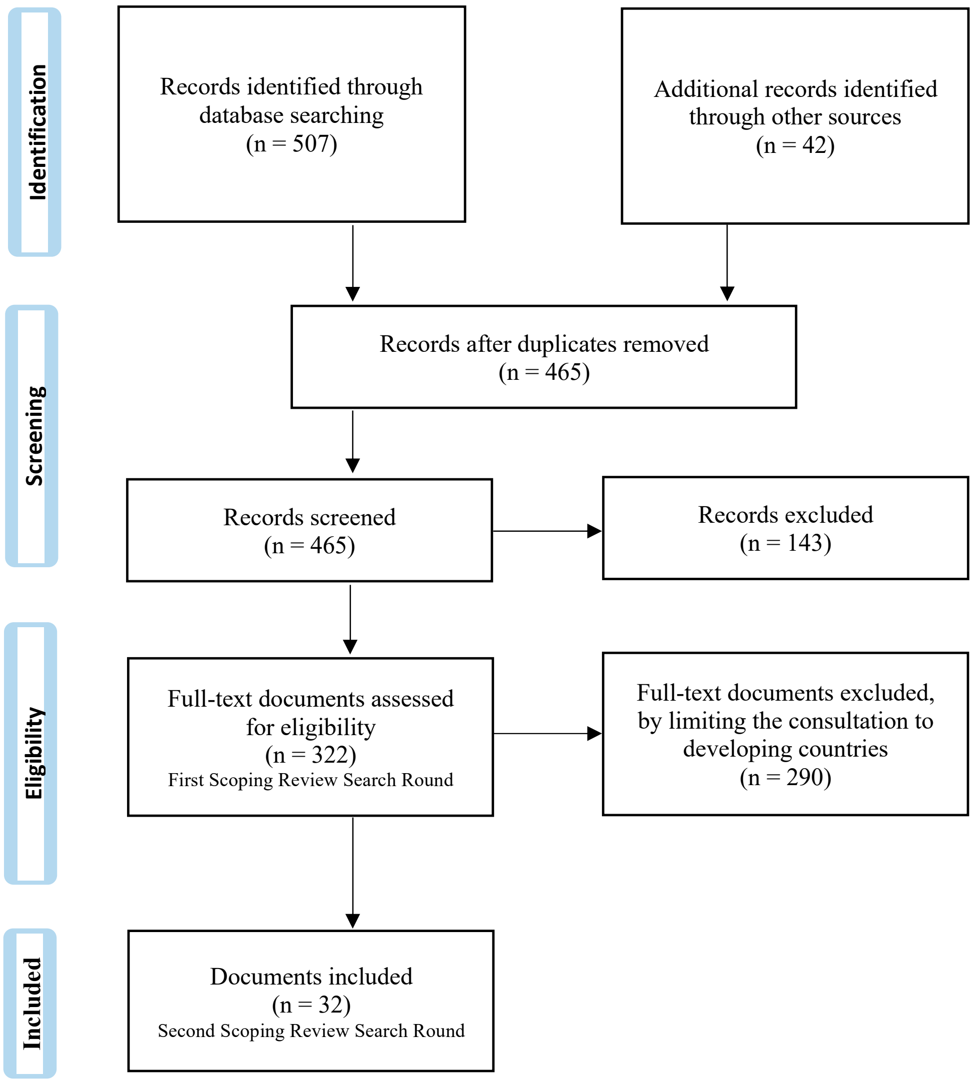

Figure 1. PRISMA flow diagram for the scoping review process of agricultural extension.

The selection of keywords and synonyms was carried out by the literature previously reviewed and included in the introduction of this document. In the initial search, keywords were selected based on their pertinence to the subject matter, as established in the introductory section. Using keywords such as "agricultural", "technology transfer", "extension", "farmer training", and "diffusion" in combination with "adoption" OR "implementation" OR "technology uptake" yielded a robust pool of studies. "Technology transfer" was included as a synonym used to capture the broader context of extension services. A total of 549 studies were identified. After removing 84 duplicate articles, 465 articles were shortlisted. A further review of these articles showed that 143 did not address the guiding questions under a Population, Concept, and Context (PCC) approach [38], which led to defining a 10-year observation window, resulting in a selection of 322 titles whose keywords were reviewed under bibliometric analysis.

To enhance the specificity of our search in the second round, terms such as "developing countries" OR "low-income countries" OR "emerging economies" were integrated, fine-tuning the scope and yielding 290 titles, which included a total of 32 documents whose keywords, titles, and summaries were analyzed (Figure 1).

2.3.1. Bibliometric Analysis

A bibliometric analysis is a powerful quantitative method employed across many disciplines, including the field of agricultural extension, to scrutinize publication patterns and extract quantifiable insights from the academic literature [45,46]. In our study, this technique is applied to distill data that address the guiding questions of our scoping review.

Publications pertinent to our inquiry, collected from two rounds of keyword searches, were meticulously organized into an Excel spreadsheet. Titles, sourced in Research Information Systems (RIS) format, were cataloged by the year of publication, facilitating the extraction of specific information. This methodical organization provided an in-depth understanding and synthesis of the material. The refined dataset was then introduced into VOSviewer version 1.6.20, a specialized software tool for constructing and visualizing bibliometric networks. This enabled us to explore the interconnections among articles, authors, abstracts, and keywords, highlighting patterns of collaboration and thematic prevalence [47,48]. In addition, VOSviewer's data mining features assisted in revealing networks of correlated keywords, underscoring the bibliometric relationships integral to the broader corpus of academic literature.

2.3.2. Analysis of the Extracted Data

A qualitative review of the collated data was undertaken following the bibliometric analysis. This involved a thematic examination of the literature to discern the various disciplines contributing to agricultural technological extension in developing countries. This step is of paramount importance as it aids in appreciating the multifaceted aspects of the rural context that are inextricably linked to technological extension. Such an analysis illuminates the spectrum of scholarly discourse, from on-the-ground practicalities to overarching policy considerations, thus enriching our understanding of the complexities within agricultural extension services.

3. Results

This section unfolds in two parts: first, a detailed description of the bibliometric analysis, and second, an exploration of the guiding questions through the lens of the collected literature, to enrich the corpus of knowledge.

3.1. Results of the Bibliometric Analysis

3.1.1. First Scoping Review Search Round

The initial search yielded 322 documents, predominantly articles, which accounted for the vast majority, 87.9%. Most of the articles indicate rigorous research activities and significant knowledge generation in the domain of agricultural technological extension (Figure 2).

Figure 2 illustrates the types of documents gleaned from the first search round, ranging from peer-reviewed articles to other scholarly contributions. The graph shows a predominance of articles, underscoring the dynamic nature of research in this field. Reviews, accounting for 6.5%, provide comprehensive syntheses of current knowledge, while at 4.3%, conference papers reflect recent trends and advances. Book chapters and data articles (0.9% combined) contribute substantially by offering a rich theoretical backdrop and essential empirical data. The scant presence of editorials (0.3%) underscores a field heavily invested in practical research applications rather than reflective commentary.

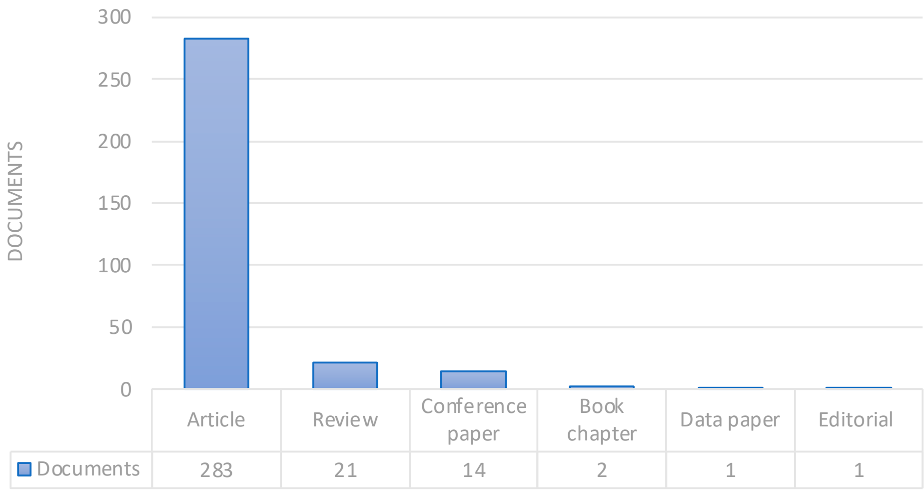

Figure 2. Bibliography identified in the first ScR search round, organized by the type of document.

Figure 3 presents the geographic and temporal distribution of the existing literature in the field of technological extension in agriculture, according to the first search round of the ScR, providing a quantitative overview of academic output over the past decade. The geographic and temporal mapping of the literature—although not explicitly depicted here—reveals the global spread and temporal evolution of research outputs, highlighting the significant contributions from countries like the United States, China, and Germany and also pinpointing research attention from African countries such as Kenya, Ethiopia, and Tanzania, which underscores the practical application in contexts most relevant to the study's focus. Temporally, the overall trend indicates increased publications over the past ten years, with notable surges in 2020 and 2022.

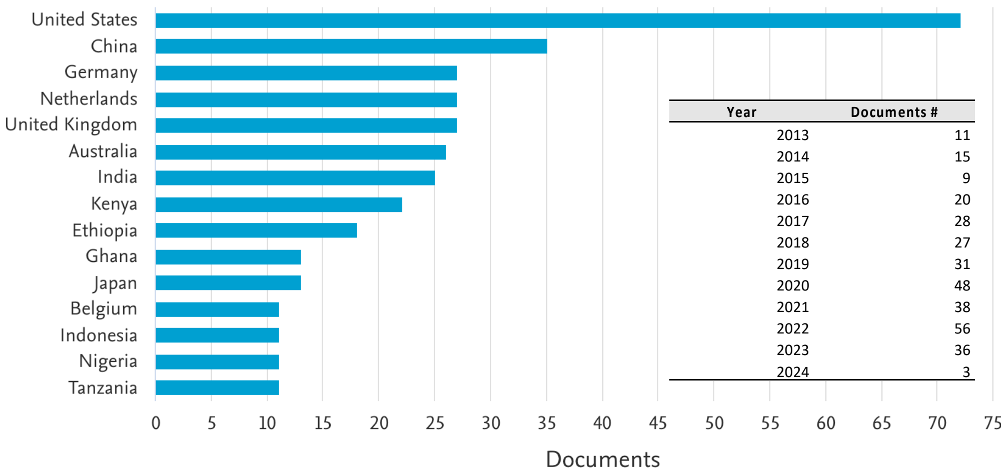

Figure 3. Geographic and temporal distribution of the literature from the first ScR search round.

As shown in Figure 4, the analysis of interconnected keywords reveals that agricultural extension and technological adoption are central and highly interrelated concepts within the literature on agricultural practices in developing countries. The mapping positions sustainability and food security at the epicenter, entwined with governance and policy, emphasizing the need for multifaceted extension strategies that are attuned to the myriad of socioeconomic, educational, and environmental factors. This interpretation helps establish a theoretical foundation for the literature review, identifying key research and policy integration areas.

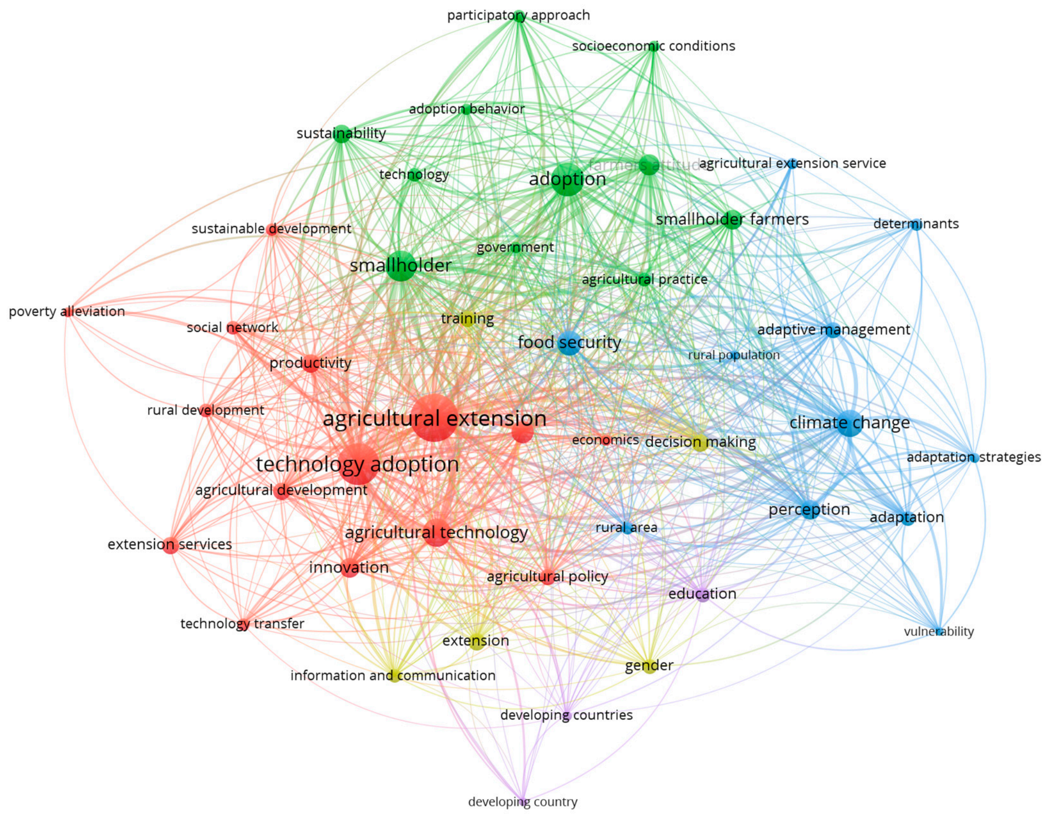

Figure 4. Recurrent and interconnected keywords in the first ScR search round.

3.1.2. Second Scoping Review Search Round

After evaluating the full texts to determine their eligibility, 30 articles, 1 book chapter, and 1 review were obtained, for a total of 32 documents included (Figure 1). The qualitative analysis of the extracted data informs the thematic distribution of literature across diverse disciplines within the agricultural technological extension. It unveils the complexity of the rural setting, demanding a holistic approach that accounts for a spectrum of elements ranging from cultural practices to technological aptitudes (Table 1).

Table 1. Subject areas, authors, and studies included in the ScR of agricultural extension.

Subject Area	Themes and Interpretation	#	Documents/Papers Included *
Social Sciences	This is the most represented category, suggesting that a significant portion of the literature on agricultural extension and technology adoption in developing countries addresses social aspects, which could include topics such as technology adoption, social dynamics, and community development.	18	[13,14,49–64]
Economics, Econometrics and Finance	Nearly a quarter of the documents focus on economic and financial aspects, underscoring the importance of economic viability, financial incentives, and cost-benefit analysis in the adoption of agricultural technologies.	17	[11,14,51,53,55,57–60,62,65–71]
Agricultural and Biological Sciences	This proportion highlights the focus on crop biology, genetic improvement, plant nutrition, pest and disease control, and other biological issues that are fundamental to technological extension in agriculture.	15	[11,49,52,55,56,58–60,63,65–67,70,72,73]
Environmental Science	The significant presence of documents in this area indicates that environmental sustainability, natural resource management, and adaptation to climate change are relevant aspects of agricultural extension.	10	[55,56,58–61,64,73–75]

Table 1. *Cont.*

Subject Area	Themes and Interpretation	#	Documents/Papers Included *
Business, Management and Accounting	A fraction of the documents relates to business management, which may include studies on farm technology management, leadership and organization of agricultural cooperatives, and market strategies.	5	[50,54,55,71,76]
Other areas	The combined areas of Medicine, Psychology, Veterinary, and Multidisciplinary make up the smallest proportion, indicating that although these fields contribute to the topic, they are less central compared to the social, economic, and agricultural sciences.	4	[55,74,76,77]

* The included documents may be present in different thematic areas.

The number of studies in social sciences (26.1%), economics (24.6%), and agricultural and biological sciences (21.7%) highlights the convergence of socioeconomic and biotechnological factors in the adoption of new technologies. The considerable attention given to environmental science (14.5%) emphasizes the importance of sustainability and climate change adaptation in agricultural practices (Figure 5).

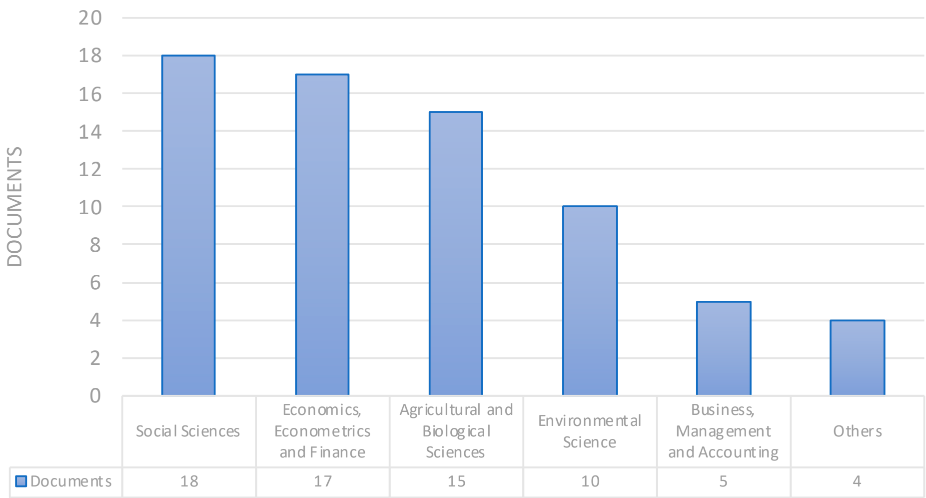

Figure 5. Bibliography identified in the second ScR search round, organized by subject area. The included documents may be present in different thematic areas.

The compilation of documents emphasizes the necessity of transforming agricultural extension from a linear transfer of knowledge to an integrative, participatory process. The dialogic interaction between extension agents and farmers emerges as a core element in the sustainable adoption of agricultural technologies. This relational dynamic underscores the need for a framework responsive to each farming community's socio-economic and cultural peculiarities.

Moreover, the discussion of extension strategies delineates a landscape wherein traditional methods are juxtaposed with innovative models. The analysis advocates for reforms prioritizing adaptability and responsiveness, enabling the effective dissemination and application of sustainable agricultural practices.

In the examination of the field of agricultural technological extension, Figure 6 offers a macro-level overview of the global research landscape. It should be noted that this figure does not necessarily represent all developing countries. The analysis points to Belgium and the United States as leading contributors to this body of knowledge, which might reflect their investment in research or a particular inclination toward developing agricultural extension methodologies in developing countries. China, Germany, and Ghana also appear to be significant contributors, signaling a potentially rising interest in or ongoing initiatives within these nations. The inclusion of countries such as Uzbekistan, India, and even Colombia, albeit with fewer documents, indicates a diverse geographic spectrum of research and reflects local efforts to develop strategies for transferring and adopting agricultural technologies tailored to their specific needs, or at least to understand this dynamic (Figure 6). The temporal distribution shows variability in the number of documents over the years, which could reveal changes in funding dynamics, research interests, and global events impacting academic production.

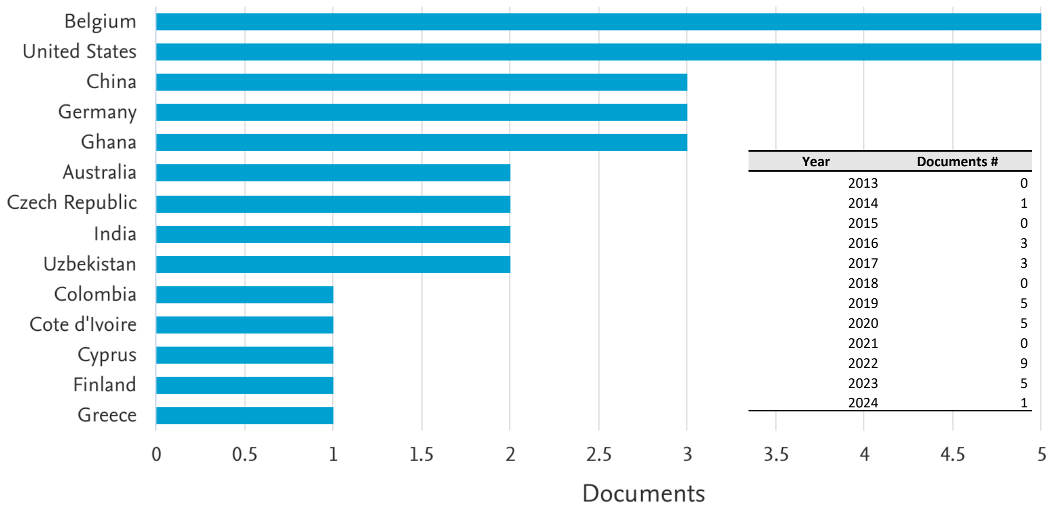

Figure 6. Geographic and temporal distribution of literature from the second ScR search round.

Figure 7 presents the intricate web of terms prevalent in the corpus of literature, with "technology adoption" taking center stage. This central node indicates a strong academic focus on the mechanisms and strategies that underpin the uptake of new agricultural technologies in the developing world. The network also elucidates the close relationship between "agricultural extension", "innovation", and "farmers", delving into the dialogues around how extension services act as a catalyst for farmers to embrace new practices.

The connection between "technology transfer", "agricultural policy", and "crop production" highlights how policy frameworks can either facilitate or impede technological diffusion in agriculture, directly affecting crop yields and production practices. Moreover, the proximity of "social learning", "social network", and "economic analysis" in the discourse underscores that adoption is deeply entrenched within complex socio-economic contexts, encompassing a broad spectrum of learning modalities, community interactions, and economic factors (Figure 7).

These visual representations underscore the pivotal role of cross-disciplinary approaches in agricultural extension, illustrating the need for strategies that are not only technically sound but are also socio-culturally and economically tailored. The analysis reveals that enhancing agricultural extension, particularly in the context of developing countries, demands a comprehensive, multifaceted approach that transcends traditional methods. Notably, the keyword network in Figure 7 lacks terms related to the environment or sustainability—such as "poverty alleviation", "sustainable development", "climate change", and "adaptive management"—which are prominent in Figure 4.

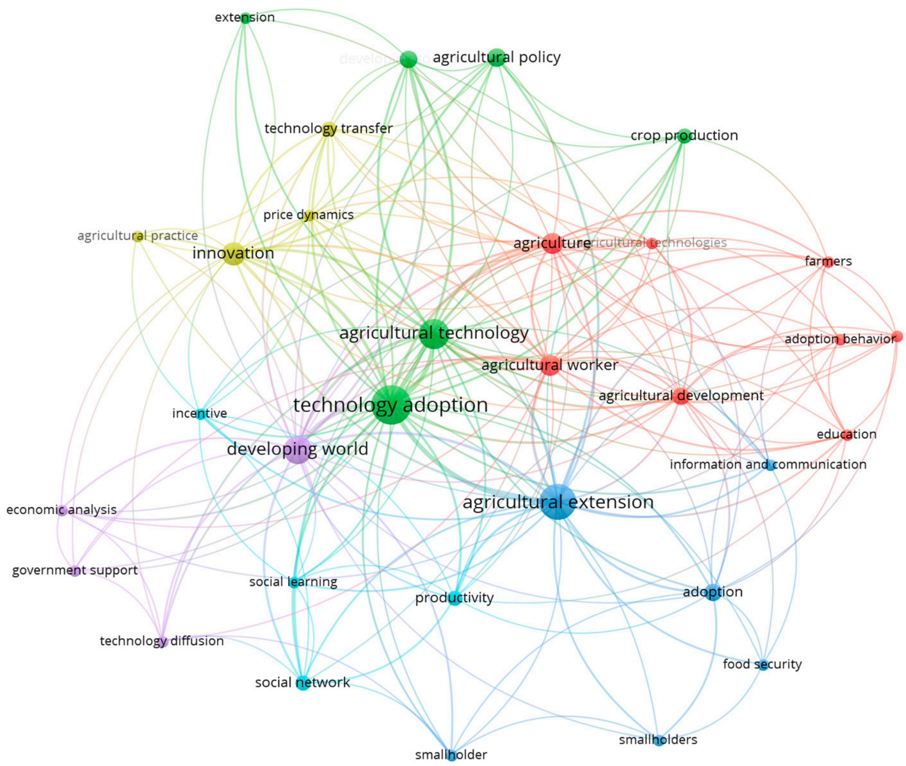

Figure 7. Recurrent and interconnected keywords in the second ScR search round.

3.2. Findings According to the Guiding Questions (GQ) of the Scoping Review

The scoping review offers a comprehensive overview of various elements within technological extension strategies in agriculture for developing countries, the impact of cultural, economic, and political differences on the implementation and adoption of agricultural technologies, the critical factors that influence the effectiveness of technological extension strategies, and the determinants affecting extension services related to the uptake of technology in sustainable agriculture. Table 2 presents a synthesized compilation of the key findings, organized by guiding questions (GQ), along with the corresponding references.

Table 2. Answers to the Guiding Questions (GQs) based on the ScR and bibliographic background.

GQ	Findings	References
What principles underpin the technological extension strategies employed in the agricultural sector of developing countries?	Education and Training: Emphasis on informal educational processes directed at the rural population as a means to improve agricultural efficiency and productivity. Community Participation: The ScR reflects a participatory approach, where farmers are seen as active partners in the learning and technology adoption process rather than passive recipients of information. Structural Support: Frequent references were identified to structural support, including economic analysis and governmental support, as critical factors in the successful adoption of agricultural technologies. Multidisciplinary: The distribution of documents by thematic area showed that social sciences, economics, and agricultural and biological sciences are closely interconnected in the literature on technological extension, highlighting the relevance of a multidisciplinary and holistic approach. Sustainability and Food Security: The need to link technology adoption with long-term outcomes in terms of sustainable agricultural practices. Sustainability and food security are intrinsically interdependent and must be considered as such in technological extension strategies.	[13,14,52–58,61–64,78]

Table 2. *Cont.*

GQ	Findings	References
How do cultural, economic, and political variances influence the implementation and assimilation of agricultural technologies?	The ScR evidence that cultural, economic, and political differences are determinant and crucial in the adoption of agricultural technologies: Culture: Aligning technologies with traditional practices and values increases acceptance by farmers. Economy: Technological adoption is sensitive to cost and perceived value. Economic incentives and access to credit are key catalysts. Policy: Effective extension policies are those that support training and provide infrastructure, promoting an environment conducive to technological adoption. Bidirectional Communication: A two-way approach, where local and scientific knowledge are exchanged, strengthens the relevance and application of agricultural technologies. Inter-organizational Collaboration: Synergy between extension workers and other rural development entities amplifies the effectiveness of technological adoption strategies. Agricultural Diversity: Recognizing and addressing the diversity of agricultural communities through tailored strategies enhances technology adoption and sustainability. These findings point to the need for technological extension strategies that are integrative and adaptive to the sociocultural and economic realities of farmers in developing countries.	[6,9,11,14,22,51,53,55,57–60,62,65–71,79]
What are the critical factors that influence the efficacy of technological extension strategies in the agricultural sector of developing countries?	Cultural Integration: Respect and integration with traditions and local knowledge, avoiding impositions, and promoting adaptive approaches that reflect the diversity of rural thought and action. Community Participation: The importance of active inclusion of farmers and consideration of their opinions and experiences are fundamental. Strategies that favor collaboration and the exchange of ideas between farmers and extension workers tend to be more effective. Use of participatory approaches, where farmers are seen as active agents rather than passive recipients in the learning and technology adoption process as well as the information transfer. Environmental and sustainability awareness: The need for programs that prioritize sustainability and consider the interdependence of agricultural communities with their natural ecosystems that are more likely to be adopted and maintained over the long term. Economic Viability: Technological extension must offer solutions and technologies that are economically accessible for them to be adopted by farmers. Furthermore, extension agents should consider the economic reality of farmers, specifically socio-economic conditions, that can increase their likelihood of technology adoption as well as potentially improve income and quality of life. Interdisciplinarity: Collaboration between different disciplines and sectors, ranging from agronomy to sociology, enriches extension strategies and ensures that the complex and varied needs of rural communities are addressed. Flexibility and Adaptation: The importance of the ability of extension strategies to adapt to changes, recognize the heterogeneity of farmer groups, and consider local contexts for the long-term success of adopting agricultural technologies.	[13,14,49–64,77,80]

Table 2. *Cont.*

GQ	Findings	References
How do extension services impact the adoption of technologies aimed at sustainable agricultural practices?	Facilitation of Adoption: Extension acts as a catalyst for technological adoption, serving not just as a technology transfer channel but also as a support system that integrates adoption practices into existing agricultural operations, taking into account the necessary adaptation and local context. Bidirectional Communication: Effective extension relies on bidirectional communication, where the knowledge and experiences of farmers are as important as the technical information provided by extension workers. This exchange encourages the adaptation and customization of technologies to the local and specific conditions of the communities. Networks and Cooperation: Communication and cooperation networks among farmers, extension workers, and technology providers are fundamental. Extension strategies should leverage these networks to improve the diffusion of technologies and support informed decision-making. Management of Critical Factors: The need to recognize and manage critical factors that can influence technological adoption, such as farmers' skill limitations, the relevance of innovations, public policy, and environmental and market settings.	[10–12,49–51,55,56,58–61,63,64,73–75,77,81]

4. Discussion

The Scoping Literature Review (ScR) has highlighted that the process of technological extension in agriculture within developing nations is intrinsically complex, with profound implications for both the uptake of technological innovations and the sustainable progression of the agricultural sector. The effectiveness of the extension, as defined by Loevinsohn et al. (2013) [10], Takahashi et al. (2020) [11], Martínez, (2022) [12], and Acheampong et al. (2024) [13], is contingent upon their capacity to assimilate and adapt novel practices within established systems, necessitating a transition in the role of extension agents from simple transmitters of technology to active facilitators that foster bidirectional exchange and empowerment [14].

Resonating with insights from BenYishay and Mobarak (2019) and Walisinghe et al. (2017) [62,69], our findings endorse a paradigm shift in extension services, urging the cultivation of inclusive systems that underpin adoption through mutual learning and shared experiences. This evolution promotes a participatory model where the empirical knowledge of farmers becomes a cornerstone in the technological design process [81,82]. This aligns with literature advocating for a farmer-centric approach to co-creating solutions [73,83,84], and employs living labs to develop collaborative and sustainable solutions tailored to the needs of producers and rural communities [85].

The analysis also identified significant socioeconomic and agroecological barriers influencing technological adoption [37,60]. The nuanced challenges faced by small-scale farmers, such as prohibitive input costs and the necessity for sustainability certifications [86], necessitate that extension systems be responsive to local economic contexts and the complexities of agricultural value chains [33,59].

The discussion also underscores the crucial role of extension in developing sustainable agriculture. With the sector experiencing transformative changes—including fiscal challenges, the increased role of private enterprises, and global shifts in agriculture—the discourse demands a reevaluation of extension strategies [34,63]. Reforms must be implemented to address prevailing issues such as misaligned extension messages and extension workers' lack of professional experience [22].

Our ScR underscores the imperative for a comprehensive framework integrating social, environmental, and economic factors into extension methodologies. An integrated approach aligns with scholarly discourse that calls for extension strategies to be culturally sensitive and adaptable to the varied needs across rural landscapes [55,56,58–60,74].

Finally, the findings from the ScR reaffirm the need for a holistic approach to agricultural technological extension. Such a model should be marked by inclusivity, flexibility, and active engagement from farmers, tailored to navigate the intricate dynamics of agriculture in diverse and constantly changing environments. This reconceptualization of extension services should be aimed at promoting sustainable agricultural practices, ultimately enhancing the livelihoods of rural communities.

4.1. Proposed Theoretical Perspective

Combining the systematic review with bibliographic insights and practical experience, this work introduces the "Integrative Extension and Technological Adoption Model in Sustainable Agriculture" (IETAMSA). IETAMSA champions a systemic and collaborative method, spotlighting the vital interplay and feedback across the spectrum of participants in the agriculture extension and tech adoption arena. The model asserts that impactful extension is a multifaceted venture, requiring engagement across various dimensions that are foundational to its success (Figure 8):

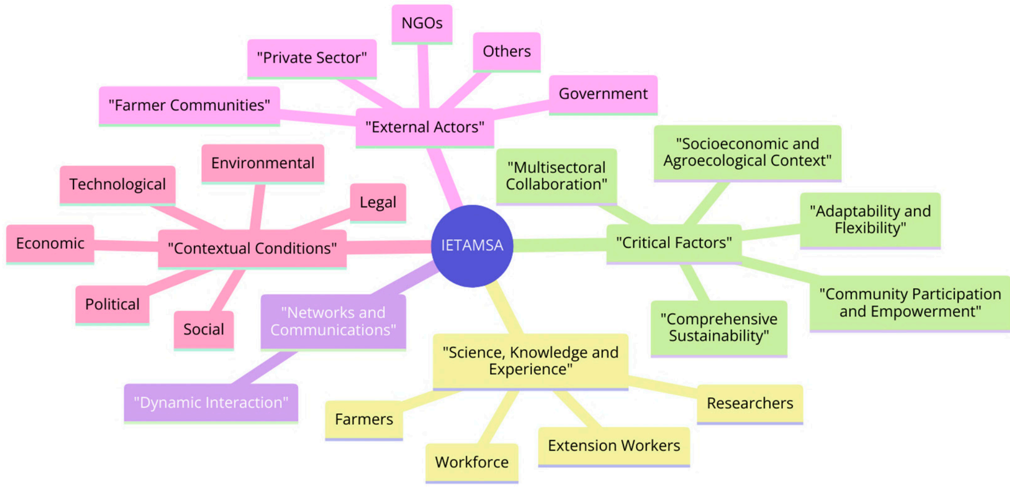

Figure 8. Mindmap illustrating the proposed theoretical perspective of the Integrative Extension and Technological Adoption Model in Sustainable Agriculture (IETAMSA).

IETAMSA posits that effective extension is inherently a multidimensional process, one that must encompass the following foundational dimensions:

4.1.1. Science, Knowledge, and Experience

Underpinning technological extension strategies and scientific research form the foundation for innovation in agricultural practices [59,60,63]. Yet, progress relies on weaving local know-how with empirical farmer insights, ensuring that scientific advancements are relevant, embraced, and tailored to the unique fabric of local communities [11,69]. This confluence of academia and on-the-ground experience enriches the evolution of technological adoption. It aligns it with the fluid dynamics of agricultural life, encompassing all key players, from producers to practitioners [57].

4.1.2. Networks and Communications

Crucial for spreading knowledge and innovations, robust communication networks enable feedback and collaborative learning [6,11]. Such networks interlink farmers, extension agents, and scholars, underpinning robust support systems and fostering resilient, adaptable agricultural practices. This dynamic interchange transcends mere information exchange, spurring an evolving network of knowledge [6,11,60].

4.1.3. Critical Factors

The handling of critical factors is instrumental in fostering or inhibiting technology adoption. Strategically addressing these factors is key to crafting effective extension methodologies and integrating lessons from multidisciplinary experiences [84]. The categories of critical factors identified in the ScR, bibliographic background, and the authors' empirical experience are as follows:

- Multisectoral collaboration: Vital for devising accessible, relevant technological solutions, this dimension involves diverse development stakeholders—from private entities to grassroots collectives—championing collaborative innovation [6,14,49,55,57,64].
- Socioeconomic and agroecological context: Acknowledging each region's distinct characteristics ensures technologies are aptly tailored, promoting contextualized rather than one-size-fits-all applications [14,49,52,55].
- Adaptability and flexibility: A malleable, responsive extension system is essential to navigating market, environmental, and innovative landscapes [6,60,81].
- Community participation and empowerment: Engaging communities in the decision-making and design of extension strategies fosters empowerment and capacity-building at the local level [6,50,55,57,59].
- Integral sustainability: Technological adoption assessments should balance economic viability with contributions to environmental integrity and societal well-being, advocating for equitably sustainable agricultural progress [55,56,58,74].

4.1.4. Contextual Conditions

The milieu of agricultural practice and technology extension is shaped by an intricate web of political, economic, social, technological, environmental, and legal factors [20]. Recognizing this complexity, IETAMSA underscores that the path to a sustainable agricultural sector is paved with nuanced understanding and bespoke responses to these multifaceted contextual conditions. Diverse agricultural communities depend on the sympathetic alignment of extension strategies with their unique circumstances—a challenge that calls for a sophisticated, granular approach to developing and implementing interventions [58,69,77].

4.1.5. External Actors

The nexus of IETAMSA's success hinges on the synergy of various external actors. Governments, the private sector, NGOs, and farming collectives contribute vital threads to the support necessary for agricultural evolution. These stakeholders are the architects of the infrastructure and policy environment that underpin knowledge exchange and sustainable practice adoption, interlinking with contextual conditions to either bolster or stymie progress in technological uptake [14,55,77].

IETAMSA is envisioned as a living framework, dynamic and responsive, intended to empower stakeholders across the spectrum—from policymakers and development agents to the farmers themselves—to architect and realize agricultural extension initiatives that resonate with the rhythm of rural life in the developing world. It champions a philosophy of interconnectedness, seeking to foster a fertile dialogue between science, local wisdom, and the lived experience of farmers. This tapestry is woven with threads of knowledge, mutual learning, and co-created innovation, harmonizing with the unique cadences of community and the environment [6,84,87].

The envisioned model, exemplified in Figure 9, represents a sequence of integrated processes and collaborative interactions. This diagrammatic representation offers a bird's-eye view of the ecosystem of influences, illustrating how each dimension of IETAMSA interacts synergistically within the broader agricultural context. Here, the confluence of science, participatory networks, and the meticulous management of critical factors converge, fostering an agricultural milieu where sustainability, community empowerment, and technological advancement are not merely aspirational but attainable realities [6,84].

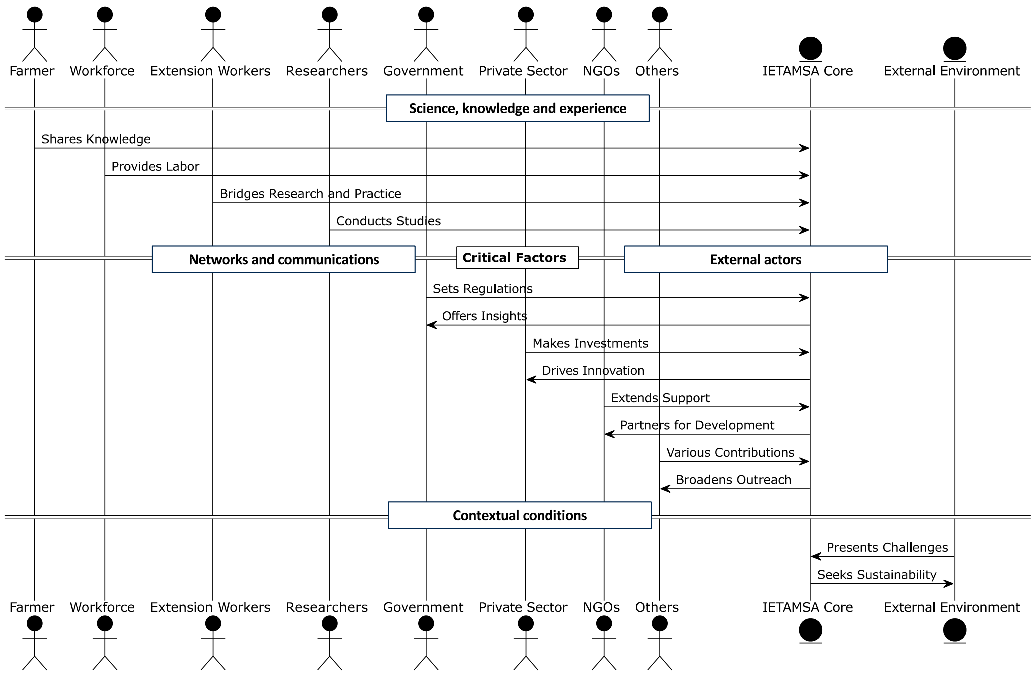

Figure 9. Sequence diagram illustrating the theoretical respective of the IETAMSA.

The theoretical framework outlined asserts a multi-layered approach to agricultural technology adoption, emphasizing the foundational role of "Science, knowledge, and experience" as the driving force for sustainable practices [13,49,76]. "Science, knowledge, and experience" are highlighted at the apex as an essential foundation that informs and supports all other levels. Building upon this, the importance of "Networks and communications", along with "Critical factors" and "External actors", is posited to operate synergistically to foster a conducive environment for the uptake of agricultural innovations [69,73,84]. Underpinning these layers, "Contextual conditions" are deemed critical [6,58], shaping the adoption and efficacy of agricultural technologies within various socio-political and environmental settings [20] (Figure 9).

Additionally, the framework highlights the Systematic Literature Review's role in enhancing the body of knowledge, aligning with the views of Walisinghe et al. (2017) [62] and BenYishay and Mobarak (2019) [69], who advocate for a more participatory, networked approach to agricultural extension. This model promotes a departure from traditional unidirectional models [30,31] to a more inclusive, bidirectional framework that capitalizes on farmer insights and a broader engagement of stakeholders in the sector. This comprehensive approach underscores the importance of considering the multifaceted nature of the agricultural landscape, from farmer involvement to the influence of policy and environmental conditions, thus offering a robust foundation for future research and practical applications in developing countries [73,81–84] and systemic thinking in agricultural innovation studies [17].

This study advances the field of agricultural extension by thoroughly examining its complex aspects, offering broad and up-to-date insights into the various factors that affect agricultural extension practices. It presents a theoretical framework designed to guide future strategic actions and policymaking in agriculture. The research strives to establish a robust basis for implementing technology extension initiatives that are tailored to the specific conditions and needs of farmers, thereby promoting sustainable growth in agriculture.

4.2. Limitations

This scoping review's reliance on a single reviewer introduces a risk of bias, as the reviewer's perspective could inadvertently shape the conclusions drawn [88]. Furthermore, the review's exclusion of non-English publications may omit valuable global insights and diverse academic discourse, narrowing the synthesized knowledge's breadth.

5. Conclusions

Drawing on the intricate tapestry woven by this scoping review, the "Integrative Extension and Technological Adoption Model in Sustainable Agriculture" (IETAMSA) crystallizes as a beacon of multidimensional strategy, propelling agricultural extension into a new era. IETAMSA emerges as an academic construct and a living, breathing framework meticulously crafted to harness the synergies of science, local wisdom, and farmer ingenuity. It is an ode to the collaborative spirit, celebrating the dynamic interplay between robust networks and communications, the critical factors of multisectoral collaboration, and the rich tapestry of contextual conditions.

This groundbreaking model is a manifesto for change. It advocates for adaptive and responsive extension systems that resonate with the heartbeat of rural communities, cultivating fertile ground for technology adoption and sustainable development. With a deep appreciation for the farmer's sociocultural, economic, and ecological milieu, IETAMSA proposes a shared vision where governmental bodies, NGOs, the private sector, and agricultural practitioners unite to nurture and uplift the rural agrarian spirit.

As we usher in this transformative paradigm, the conclusions of this comprehensive review extend beyond the page, resonating with a call to action for sustainable agriculture that is equitable, resilient, and integrated into the fabric of rural life. It is a commitment to a future where extension services transfer knowledge and weave a more prosperous, connected, and sustainable tapestry of agricultural livelihoods.

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