**The Role of Participatory Approaches in Modern Agricultural Extension: Bridging Knowledge Gaps for Sustainable Farming Practices**

**Abstract**

Participatory approaches in agricultural extension have revolutionized knowledge dissemination by fostering collaborative learning, farmer empowerment, and the co-creation of context-specific innovations. Unlike traditional top-down extension models, participatory methodologies emphasize mutual learning, where farmers, researchers, and extension agents engage in dynamic exchanges to develop adaptive and sustainable agricultural practices. These approaches have proven effective in promoting climate-smart agriculture, integrated pest management, soil and water conservation, and agroecological transitions, ensuring resilience in the face of environmental and socio-economic challenges. The implementation of participatory extension faces significant barriers, including institutional rigidity, policy constraints, resource limitations, socio-cultural biases, and gaps in extension agent training. Addressing these challenges requires strategic interventions such as policy reforms to institutionalize participatory models, strengthening public-private partnerships to leverage financial and technical expertise, and investing in digital technologies to enhance accessibility and knowledge-sharing. The integration of artificial intelligence, big data analytics, and mobile-based advisory services has further expanded the potential of participatory extension, enabling real-time decision-making and personalized agricultural advisories. Future must prioritize farmer-led innovation networks, climate-resilient extension models, and participatory market linkages to ensure holistic agricultural development. Fostering multi-stakeholder collaboration among governments, research institutions, NGOs, and farmer organizations is critical to scaling up participatory extension services. Expanding the role of community-driven agroforestry, sustainable land management, and localized climate adaptation strategies will further enhance the impact of participatory agricultural extension. Ultimately, participatory approaches offer a sustainable and inclusive pathway for agricultural transformation, ensuring that extension services are responsive to farmer needs, environmentally sound, and economically viable. By integrating participatory methodologies with emerging agricultural technologies and policy support, the future of agricultural extension can effectively empower smallholder farmers, improve food security, and promote long-term sustainability in global agriculture systems.

**Keywords:** *Participatory, Extension, Agriculture, Sustainability, Knowledge-sharing, Farmer-led, Innovation*

**1. Introduction**

**A. Importance of Agricultural Extension in Modern Farming**

Agricultural extension has played a crucial role in enhancing farming productivity, improving rural livelihoods, and promoting sustainable agricultural practices worldwide (Table 1) (Sahu *et.al.,* 2023). Extension services serve as the primary channel for disseminating scientific knowledge and technology to farmers, ensuring the adoption of improved practices that enhance crop yields, soil health, and overall farm profitability. Extension services have evolved from top-down, expert-driven models to more participatory and farmer-centric approaches that recognize the importance of localized knowledge. Traditional extension models primarily focused on the one-way transfer of knowledge from research institutions to farmers, often neglecting the dynamic and interactive nature of agricultural innovation systems. The significance of agricultural extension has been amplified in recent years due to global challenges such as climate change, food insecurity, land degradation, and rural poverty (Smith *et.al.,* 2020). Modern extension systems aim to bridge the gap between scientific research and practical field application, ensuring that farmers have access to the latest agricultural advancements, including precision farming, climate-resilient crop varieties, and integrated pest management. Despite their critical role, conventional extension services have faced several challenges, including limited funding, inadequate human resources, and ineffective communication channels. These constraints have necessitated the adoption of more inclusive and participatory approaches that actively involve farmers in decision-making processes and knowledge creation. In the contemporary era, agricultural extension is not only about technology transfer but also about empowering farmers as active stakeholders in the agricultural knowledge system (Chowdhury *et.al.,* 2014). By fostering collaboration among farmers, researchers, policymakers, and private sector stakeholders, modern extension systems promote innovations that are locally relevant and economically viable.

**B. Need for Participatory Approaches in Agricultural Extension**

The traditional extension paradigm, which relied on a linear transfer of knowledge from research institutions to farmers, has often been criticized for being ineffective in addressing the complex realities of smallholder farming systems. The limitations of the conventional approach stem from its inability to consider diverse agroecological conditions, farmer knowledge, and local socio-economic constraints (Lacombe *et.al.,* 2018). Participatory extension approaches prioritize the active involvement of farmers in the extension process, recognizing them as key contributors rather than passive recipients of information. Participatory agricultural extension is based on principles of experiential learning, mutual knowledge exchange, and empowerment. It fosters an environment where farmers, extension workers, and researchers collaborate in problem identification, experimentation, and innovation. This approach is particularly crucial in the context of sustainable farming, as it enhances the relevance and applicability of agricultural technologies by ensuring that they are tailored to local conditions and farmer needs. Unlike top-down models, participatory approaches promote social learning and community engagement, leading to the development of resilient and adaptive farming systems (Stringer *et.al.,* 2006). Several participatory extension models have emerged over the years, including Farmer Field Schools (FFS), Participatory Rural Appraisal (PRA), and Participatory Technology Development (PTD), each emphasizing farmer-led decision-making and knowledge sharing. Farmer Field Schools, have been widely successful in promoting integrated pest management, organic farming, and agroecological practices by enabling farmers to experiment, learn from each other, and make informed decisions based on field observations. PRA methods facilitate rural communities in mapping out their agricultural challenges, resources, and priorities, thereby fostering bottom-up solutions that are context-specific and sustainable. The adoption of participatory approaches in extension services also addresses the gender and equity dimensions of agricultural development. Women, who constitute a significant portion of the agricultural workforce, have historically been marginalized in extension programs. By incorporating participatory methods, extension services can ensure greater inclusivity, acknowledging the unique knowledge and experiences of women farmers in areas such as seed selection, post-harvest processing, and nutrition-sensitive agriculture (Fadda *et.al.,* 2020). Participatory approaches enhance the scalability and sustainability of agricultural innovations. Unlike externally imposed solutions that may fail to gain farmer acceptance, technologies developed through participatory processes have higher adoption rates and long-term viability. The integration of digital tools, such as mobile-based advisory platforms and social media networks, has further strengthened participatory extension by enabling real-time knowledge sharing and collaborative decision-making among farmers (Mapiye *et.al.,* 2023).

**Table:1** Participatory Approaches in Agricultural Extension (Source: Chowdhury *et.al*., 2014, Fadda et.al., 2020)

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| --- | --- | --- | --- |
| **Approach** | **Objective** | **Methodology** | **Key Benefits** |
| **Farmer Field Schools (FFS)** | To enhance farmers' knowledge through experiential learning. | Group-based, season-long field experiments and discussions. | Empowers farmers with decision-making skills and sustainable farming practices. |
| **Participatory Rural Appraisal (PRA)** | To involve local communities in assessing rural situations. | Uses participatory tools like mapping, ranking, and discussions. | Enhances community engagement and ensures bottom-up planning. |
| **Farmer-to-Farmer Extension** | To transfer knowledge and skills between farmers. | Experienced farmers train and mentor other farmers. | Strengthens peer learning, cost-effective, and improves adoption rates. |
| **Participatory Technology Development (PTD)** | To develop agricultural technologies suited to local conditions. | Collaboration between farmers, researchers, and extension agents. | Ensures farmer-friendly innovations and practical solutions. |
| **Agro-Ecosystem Analysis (AESA)** | To assess and manage agro-ecosystem dynamics. | Field observations, analysis, and participatory decision-making. | Encourages sustainable resource management and ecosystem-based farming. |
| **Participatory Learning and Action (PLA)** | To enable communities to analyze and improve their farming systems. | Iterative learning cycles with participatory discussions and activities. | Strengthens community ownership and innovation. |
| **Community-Based Extension** | To decentralize agricultural extension services. | Local groups organize and implement extension activities. | Enhances localized knowledge sharing and self-reliance. |
| **Innovation Platforms** | To facilitate collaboration among agricultural stakeholders. | Multi-stakeholder forums for joint problem-solving and knowledge exchange. | Promotes co-innovation and strengthens partnerships. |
| **Participatory Video (PV)** | To document and share agricultural knowledge visually. | Farmers create and disseminate videos on farming practices. | Enhances accessibility of knowledge and farmer-to-farmer learning. |
| **Village Knowledge Centers (VKC)** | To provide digital agricultural knowledge in rural areas. | ICT-based centers offering real-time information to farmers. | Bridges the digital divide and improves decision-making capacity. |

**2. Participatory Approaches in Agricultural Extension**

**A. Evolution of Participatory Approaches**

Participatory approaches in agricultural extension emphasize active involvement, collaboration, and shared decision-making among farmers, extension agents, researchers, and other stakeholders in agricultural development (Table 2). These approaches acknowledge farmers as key knowledge contributors rather than passive recipients of externally generated information, thereby ensuring that agricultural technologies and innovations are better adapted to local needs and conditions. The evolution of participatory extension models can be traced to the dissatisfaction with traditional, top-down extension systems that focused primarily on linear knowledge transfer from experts to farmers (Olayemi *et.al.,* 2021). Extension services followed a technology-transfer model rooted in the diffusion of innovations theory, where researchers and policymakers assumed that farmers needed to adopt new technologies for agricultural progress. This expert-driven approach often disregarded indigenous knowledge, farmer experiences, and local agroecological conditions, leading to low adoption rates and resistance to externally imposed solutions. The rise of participatory agricultural extension emerged as a response to these limitations, influenced by broader shifts in development paradigms advocating for grassroots empowerment, decentralized governance, and community-led decision-making. The 1970s and 1980s saw the introduction of participatory learning and research methodologies, such as Participatory Rural Appraisal (PRA), Participatory Technology Development (PTD), and Farmer Field Schools (FFS), which prioritized farmer-led experimentation, social learning, and adaptive management. These approaches challenged the conventional wisdom that scientific institutions alone could generate agricultural knowledge and instead promoted interactive learning processes that integrated scientific research with experiential knowledge from farmers. By the 1990s and early 2000s, participatory approaches were further institutionalized by development agencies, research organizations, and government extension programs seeking to improve the impact, inclusiveness, and sustainability of agricultural innovations. Today, participatory extension approaches have expanded to include digital tools, community-driven initiatives, and multi-stakeholder platforms that foster greater connectivity and collaboration across the agricultural knowledge system (Yang *et.al.,* 2023).

**B. Foundations and Models of Participation in Extension**

The foundations of participatory agricultural extension are deeply rooted in development studies, rural sociology, and innovation systems theory. Several frameworks have shaped the conceptualization and implementation of participatory approaches in extension services, each emphasizing different aspects of farmer engagement, knowledge co-creation, and collective problem-solving. One of the earliest theoretical influences is Participatory Action Research (PAR), developed by scholars such as Paulo Freire and Kurt Lewin, which promotes the idea that knowledge generation should be an iterative, collaborative process involving those directly affected by the issues being studied. This theory has significantly influenced participatory extension methods, advocating for farmer-led inquiry, adaptive experimentation, and iterative learning cycles (Douthwaite *et.al.,* 2017). Another foundational theory is the Farmer First Paradigm, which emerged in response to the shortcomings of top-down agricultural extension models. This paradigm, popularized by Robert Chambers and his colleagues, argues that farmers should be at the centre of the innovation process rather than treated as passive adopters of technologies (Letty *et.al.,* 2012). It challenges the conventional hierarchical structure of knowledge dissemination and instead promotes farmer-led learning, local adaptation of technologies, and inclusive decision-making. Closely related is the Agricultural Knowledge and Information Systems (AKIS) framework, which conceptualizes agricultural extension as an interconnected system involving multiple actors including farmers, researchers, extension agents, private sector actors, and policymakers who collaborate to facilitate knowledge exchange and innovation. Unlike earlier linear models, AKIS recognizes the dynamic, networked nature of agricultural learning and emphasizes the importance of participatory interactions in driving knowledge diffusion and technology adoption.

Several practical models of participatory extension have emerged based on these theoretical foundations (Leach *et.al.,* 1996). One of the most well-known is the Farmer Field School (FFS) model, initially developed by the Food and Agriculture Organization (FAO) to promote integrated pest management. FFS operates on the principle of experiential learning, where farmers engage in hands-on experiments, peer-to-peer discussions, and group-based decision-making to improve their agricultural practices. Another widely used model is Participatory Rural Appraisal (PRA), which employs visual mapping, problem-tree analysis, and interactive discussions to facilitate community-driven agricultural planning. Participatory Technology Development (PTD) further extends these principles by fostering farmer-researcher partnerships to co-develop, test, and refine agricultural innovations based on local needs. Community-based extension models emphasize the role of farmer organizations, cooperatives, and self-help groups in extension service delivery, leveraging collective action and shared resources to enhance agricultural learning and practice.

**C. Principles of Participatory Extension Approaches**

Participatory extension approaches are guided by several fundamental principles that differentiate them from conventional top-down extension models (Hagmann *et.al.,* 1999). The core philosophy underlying participatory extension is farmer empowerment, which emphasizes the agency of rural communities in shaping their own agricultural development trajectories. These principal challenges traditional notions of agricultural extension as a process of expert knowledge transfer and instead fosters an environment where farmers actively engage in decision-making, problem-solving, and technology adaptation. Participatory extension approaches prioritize experiential and social learning, recognizing that knowledge is best acquired through direct observation, experimentation, and peer interactions. By emphasizing hands-on learning, these approaches enhance farmers’ capacity to analyze field conditions, identify solutions, and make informed decisions based on real-world experiences. Inclusivity and equity are also central to participatory extension, ensuring that historically marginalized groups such as smallholder farmers, women, and indigenous communities are actively involved in extension processes (Cook *et.al.,* 2021). Traditional extension models have often excluded women farmers despite their critical role in food production and household-level agricultural decision-making. Participatory approaches seek to rectify these disparities by incorporating gender-sensitive methodologies that recognize and address the unique constraints and contributions of women in agriculture. Participatory extension emphasizes context-specific knowledge creation, moving away from one-size-fits-all recommendations toward locally adapted solutions that take into account ecological diversity, cultural practices, and socio-economic conditions.

Another key principle is the promotion of collective action and networking, which facilitates horizontal learning among farmers and enhances the diffusion of innovations within rural communities (Monge *et.al.,* 2008). Rather than relying solely on external extension agents, participatory models encourage knowledge-sharing through farmer groups, cooperatives, and community-based organizations. This approach fosters stronger social capital, enabling farmers to access resources, markets, and institutional support more effectively. Sustainability and resilience are also integral to participatory extension, as these approaches prioritize long-term environmental stewardship, resource-efficient farming practices, and climate adaptation strategies. Unlike conventional extension programs that may prioritize short-term productivity gains, participatory methods seek to balance productivity with ecological sustainability, ensuring that farming systems remain viable for future generations. Flexibility and adaptability further distinguish participatory extension from rigid, expert-driven models (Gray *et.al.,* 2015). Given the inherent variability of agricultural systems, participatory approaches allow for continuous learning, feedback, and iterative adjustments to technologies and practices. This adaptive capacity is particularly valuable in the face of climate change, where farmers must respond to unpredictable environmental conditions and emerging challenges. By fostering local innovation and resilience, participatory extension enhances farmers' ability to experiment with new techniques, modify existing practices, and co-develop solutions that are sustainable and locally relevant. Through these guiding principles, participatory approaches in agricultural extension contribute to more effective, inclusive, and sustainable farming systems, ultimately strengthening rural livelihoods and enhancing food security.

**Table:2** Participatory Approaches in Agricultural Extension (Source: Smith *et.al.,* 2020, Cook *et.al.,* 2021)

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| **Approach** | **Objective** | **Methodology** | **Key Benefits** |
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| **Farmer-to-Farmer Extension** | To transfer knowledge and skills between farmers. | Experienced farmers train and mentor other farmers. | Strengthens peer learning, cost-effective, and improves adoption rates. |
| **Participatory Technology Development (PTD)** | To develop agricultural technologies suited to local conditions. | Collaboration between farmers, researchers, and extension agents. | Ensures farmer-friendly innovations and practical solutions. |
| **Agro-Ecosystem Analysis (AESA)** | To assess and manage agro-ecosystem dynamics. | Field observations, analysis, and participatory decision-making. | Encourages sustainable resource management and ecosystem-based farming. |
| **Participatory Learning and Action (PLA)** | To enable communities to analyze and improve their farming systems. | Iterative learning cycles with participatory discussions and activities. | Strengthens community ownership and innovation. |
| **Community-Based Extension** | To decentralize agricultural extension services. | Local groups organize and implement extension activities. | Enhances localized knowledge sharing and self-reliance. |
| **Innovation Platforms** | To facilitate collaboration among agricultural stakeholders. | Multi-stakeholder forums for joint problem-solving and knowledge exchange. | Promotes co-innovation and strengthens partnerships. |
| **Participatory Video (PV)** | To document and share agricultural knowledge visually. | Farmers create and disseminate videos on farming practices. | Enhances accessibility of knowledge and farmer-to-farmer learning. |
| **Village Knowledge Centers (VKC)** | To provide digital agricultural knowledge in rural areas. | ICT-based centers offering real-time information to farmers. | Bridges the digital divide and improves decision-making capacity. |

**3. Role of Participatory Approaches in Agricultural Knowledge Generation and Dissemination**

**A. Farmer-Centric Knowledge Exchange and Learning**

Participatory approaches in agricultural extension emphasize a farmer-centric model of knowledge exchange and learning, which shifts away from the traditional top-down dissemination of agricultural information (Singh *et.al.,* 2016). Conventional agricultural extension systems primarily followed the transfer-of-technology (TOT) model, wherein researchers and extension agents disseminated scientific knowledge to farmers, assuming that innovation adoption was a linear process. This approach has often been criticized for overlooking the experiential knowledge of farmers, which plays a crucial role in decision-making and technology adaptation. Participatory extension fosters an interactive learning environment where farmers, researchers, and extensionists engage in dialogue and mutual knowledge-sharing, leading to more effective and context-specific agricultural solutions. Farmer-centric knowledge exchange is rooted in the principles of adult learning and experiential education, where farmers actively participate in the learning process through observation, experimentation, and reflection (Hainzer *et.al.,* 2022). This method enhances farmers' ability to analyze their own agricultural systems, identify challenges, and co-develop solutions in collaboration with experts and fellow farmers. Social learning theories further reinforce the importance of peer-to-peer knowledge dissemination, where farmers learn from one another through discussion, demonstration, and collective problem-solving. Community-based extension initiatives, such as farmer-led training and cooperative learning groups, have been widely adopted to facilitate knowledge exchange, particularly in resource-constrained rural areas.

Studies have shown that participatory knowledge-sharing approaches enhance the adoption of improved agricultural practices by increasing farmers' confidence in decision-making and fostering a sense of ownership over technological innovations. Unlike top-down approaches that often result in technology rejection or poor adoption rates, farmer-driven knowledge exchange ensures that innovations are relevant, adaptable, and sustainable in local contexts (Mapiye *et.al.,* 2024). Participatory approaches recognize the social dimensions of knowledge exchange, highlighting the role of trust, community networks, and local institutions in facilitating learning and agricultural innovation. By placing farmers at the centre of knowledge-generation processes, participatory extension enhances the relevance, accessibility, and long-term sustainability of agricultural development initiatives.

**B. Co-creation of Agricultural Innovations Through Local and Scientific Knowledge Integration**

The participatory approach to agricultural extension emphasizes the co-creation of innovations through the integration of local knowledge and scientific research. This model acknowledges that farmers possess valuable experiential knowledge gained through years of practice, which can complement formal scientific research to develop more effective agricultural solutions (Meijer *et.al.,* 2015). Unlike conventional research-driven extension, which often imposes externally developed technologies onto farmers, participatory innovation systems foster a collaborative relationship between scientists, extension agents, and farming communities. Participatory Technology Development (PTD) is one of the most prominent frameworks for co-creating agricultural innovations. PTD involves farmers and researchers jointly experimenting with new technologies, assessing their feasibility under local conditions, and refining them through iterative cycles of learning and adaptation. This process ensures that agricultural innovations are not only scientifically validated but also practically viable, culturally acceptable, and economically feasible for farmers.

One of the most notable successes of local-scientific knowledge integration is seen in participatory plant breeding (PPB), where farmers and breeders collaborate to develop crop varieties that meet specific agroecological and socio-economic needs (Swiderska *et.al.,* 2018). PPB programs have been highly effective in regions with diverse farming conditions, where centralized breeding programs have struggled to produce varieties suited to local microclimates and farmer preferences. Participatory soil fertility management (PSFM) integrates farmers' traditional soil conservation practices with scientific recommendations on nutrient management, leading to more sustainable and productive farming systems. Participatory innovation co-creation extends beyond technological development to include institutional and organizational innovations. Farmer-led cooperatives, self-help groups, and community seed banks have emerged as key platforms for collective decision-making, knowledge-sharing, and resource mobilization. These grassroots institutions play a crucial role in scaling up innovations by facilitating farmer-to-farmer extension and reducing dependency on external support systems. By fostering collaboration between farmers and scientists, participatory approaches to agricultural innovation bridge knowledge gaps, enhance local adaptive capacity, and contribute to the long-term resilience of farming communities (Klerkx *et.al.,* 2010).

**C. Role of Indigenous Knowledge in Participatory Extension**

Indigenous knowledge, often acquired through generations of farming experience, is an integral component of participatory agricultural extension. Unlike conventional extension models that prioritize scientific knowledge, participatory approaches recognize the value of indigenous knowledge in shaping locally relevant agricultural practices and innovations. Indigenous agricultural knowledge encompasses a wide range of domain-specific expertise, including soil fertility management, pest control, water conservation, seed selection, and weather prediction. Participatory extension methodologies integrate indigenous knowledge by facilitating farmer-led documentation, knowledge-sharing platforms, and cross-learning exchanges between traditional and scientific knowledge holders. One of the most effective strategies for leveraging indigenous knowledge is community-based resource management, where farmers collaborate to develop locally adapted solutions for sustainable land use and natural resource conservation (Adeyanju *et.al.,* 2021).

Despite its significance, indigenous knowledge has often been marginalized in formal agricultural research and extension due to institutional biases favouring scientific knowledge systems. Participatory approaches have increasingly emphasized knowledge co-production, where indigenous and scientific expertise are combined to enhance agricultural sustainability and resilience. By validating and integrating indigenous knowledge within extension frameworks, participatory approaches ensure that agricultural innovations are not only scientifically sound but also culturally and ecologically appropriate.

**D. Farmer Field Schools (FFS) and Their Impact on Sustainable Learning**

Farmer Field Schools (FFS) represent one of the most successful participatory extension models for enhancing sustainable learning in agriculture. Originally developed by the FAO to promote Integrated Pest Management (IPM) in rice production, FFS has since been widely adopted across different agricultural sectors and regions. The core principle of FFS is experiential learning, where farmers engage in hands-on activities, field observations, and group discussions to develop problem-solving skills and adaptive capacities (Tomlinson *et.al.,* 2018). Unlike conventional extension approaches that rely on prescriptive training sessions, FFS encourages farmers to conduct their own experiments, analyze field conditions, and make evidence-based decisions. This participatory learning model has been highly effective in improving farmers' understanding of complex agroecological interactions, leading to more informed choices regarding pest management, soil fertility enhancement, and climate adaptation strategies. Research has shown that FFS contributes to long-term knowledge retention and farmer empowerment by fostering critical thinking, leadership development, and community engagement. FFS has been instrumental in scaling up sustainable agricultural practices by creating farmer-led extension networks that promote peer-to-peer learning (Kalita *et.al.,* 2019). By enhancing farmers' capacity to generate, analyze, and apply knowledge, FFS plays a crucial role in strengthening participatory agricultural extension and ensuring the long-term sustainability of farming systems.

**4. Participatory Approaches in Agricultural Extension: Methodologies and Tools**

**A. Participatory Rural Appraisal (PRA) Techniques in Extension Services**

Participatory Rural Appraisal (PRA) is an interactive and inclusive methodology widely used in agricultural extension to engage farmers and rural communities in decision-making, problem identification, and knowledge-sharing processes. Developed in the late 1980s, PRA evolved from earlier participatory approaches such as Rapid Rural Appraisal (RRA), shifting towards a more empowering and farmer-centered model. Unlike conventional extension methods that rely on expert-led interventions, PRA prioritizes local knowledge and community-driven solutions, enabling rural populations to analyze their own agricultural challenges and develop appropriate responses (Maskrey *et.al.,* 2022). The core techniques used in PRA include participatory mapping, transect walks, seasonal calendars, matrix ranking, Venn diagrams, and livelihood analysis. These tools facilitate collective learning, allowing farmers to visualize spatial and temporal aspects of their farming systems and identify priority areas for intervention. Participatory mapping, helps farmers document land-use patterns, soil fertility gradients, and water resource distribution, aiding in more targeted extension planning. Transect walks, where extension workers and farmers collaboratively assess field conditions, provide real-time insights into local agroecological challenges and potential solutions (Mengistu *et.al.,* 2022). PRA has been extensively applied in sustainable agriculture programs, especially in resource-poor farming systems where conventional extension approaches have limited reach. Studies have shown that PRA-based extension services lead to higher adoption rates of improved agricultural practices, as they are designed around farmer-identified priorities and indigenous knowledge systems. PRA fosters social learning and strengthens community cohesion, enabling collective action for resource management and climate adaptation. Challenges such as facilitator bias, time constraints, and the need for skilled practitioners have been noted in PRA implementation, necessitating ongoing training and methodological refinement (Kitson *et.al.,* 2008).

**B. Farmer-Led Research and On-Farm Trials for Technology Validation**

Farmer-led research and on-farm trials represent key participatory methodologies that enable farmers to test, validate, and refine agricultural technologies under real-world conditions. Unlike conventional research that is conducted in controlled experimental stations and later transferred to farmers, participatory research involves farmers as co-investigators, ensuring that innovations are tailored to local conditions and farming practices. Farmer-led research builds upon the principles of Participatory Technology Development (PTD), where farmers, extension workers, and researchers collaboratively develop, test, and adapt technologies based on iterative feedback loops. On-farm trials provide an effective platform for validating new crop varieties, soil fertility management techniques, pest control strategies, and water conservation practices (Toffolini *et.al.,* 2022). These trials often employ participatory varietal selection (PVS), where farmers evaluate multiple crop genotypes based on agronomic performance, resilience, and market demand. By engaging in adaptive experimentation, farmers gain firsthand experience with new technologies, increasing their confidence and willingness to adopt sustainable farming practices. Case studies from Africa, Asia, and Latin America have demonstrated that farmer-led research enhances technology adoption rates and fosters resilience in smallholder agriculture. In Malawi, participatory soil fertility management trials have led to widespread adoption of integrated nutrient management strategies, improving crop yields and soil health. Farmer-led pest management research in Southeast Asia has successfully reduced pesticide dependency through community-driven Integrated Pest Management (IPM) programs.

**C. Focus Group Discussions, Workshops, and Knowledge Sharing Platforms**

Focus group discussions (FGDs), workshops, and knowledge-sharing platforms are essential participatory tools that facilitate collective problem-solving, information exchange, and collaborative decision-making in agricultural extension. FGDs bring together small groups of farmers, extension workers, and researchers to discuss specific agricultural challenges, assess technology options, and co-develop solutions (Mulema *et.al.,* 2016). Unlike surveys or structured interviews, FGDs allow for dynamic interaction and in-depth exploration of farmer perspectives, fostering participatory learning. Workshops serve as interactive learning spaces where farmers receive hands-on training, participate in demonstrations, and engage in peer-to-peer exchanges. These participatory learning environments have been widely used in Farmer Field Schools (FFS) to enhance capacity building in areas such as soil conservation, climate adaptation, and value chain development. In many cases, workshops incorporate participatory video and storytelling techniques to document and disseminate farmer experiences, further strengthening knowledge-sharing networks. In recent years, digital knowledge-sharing platforms have gained prominence, enabling remote and real-time farmer engagement. Online farmer forums, mobile-based advisory services, and community radio programs have emerged as powerful tools for participatory extension, bridging geographic and linguistic barriers (Khan *et.al.,* 2025). These platforms enhance horizontal learning among farmers, facilitating the diffusion of context-specific agricultural innovations.

**D. Role of Digital Technologies and ICTs in Enhancing Participation**

The integration of digital technologies and Information and Communication Technologies (ICTs) into participatory extension has revolutionized knowledge-sharing, decision-support systems, and farmer empowerment. Mobile phones, SMS-based advisory services, smartphone applications, and digital farmer networks have significantly enhanced access to agricultural information and extension services. ICT-based platforms such as Digital Green, e-Choupal, and M-Kilimo have successfully connected farmers with extension agents, researchers, and markets, reducing transaction costs and improving information flow. Geo-referenced participatory mapping tools and remote sensing technologies have further strengthened participatory extension by enabling farmers to monitor soil health, water resources, and climate variability (Mathenge *et.al.,* 2022). Crowdsourced data collection platforms and citizen science initiatives have also facilitated farmer-driven research and real-time agricultural monitoring. Challenges such as digital literacy gaps, language barriers, and limited internet connectivity in rural areas continue to pose constraints to ICT-enabled participatory extension.

**E. Gender-Responsive Participatory Approaches in Agricultural Extension**

Gender-responsive participatory extension recognizes the unique knowledge, skills, and contributions of women in agriculture, ensuring that extension services are inclusive and equitable. Traditional extension models have often marginalized women farmers due to socio-cultural norms, limited mobility, and gender biases in knowledge systems. Participatory approaches, actively engage women in decision-making, technology adaptation, and leadership roles in agricultural extension. Successful gender-inclusive participatory methodologies include women-led Farmer Field Schools, self-help groups, and community-based extension networks that prioritize women's knowledge and innovation. Gender-responsive extension has been instrumental in promoting climate-smart agriculture, nutrition-sensitive farming, and micro-enterprise development among rural women. Digital platforms tailored for women farmers, such as mobile-based advisory services in India and Africa, have further enhanced gender-inclusive agricultural extension (Lahiri *et.al.,* 2024).

**5. Impact of Participatory Extension on Sustainable Farming Practices**

**A. Adoption of Climate-Smart Agriculture Through Participatory Approaches**

Participatory agricultural extension has played a critical role in fostering the adoption of climate-smart agriculture (CSA) by integrating farmer knowledge, local context, and scientific research into climate adaptation strategies. Climate-smart agriculture, as defined by the Food and Agriculture Organization (FAO), seeks to increase agricultural productivity, enhance resilience to climate change, and reduce greenhouse gas emissions. Traditional top-down extension approaches have often failed to account for the variability of agroecological conditions and farmer-specific challenges. Participatory extension methods, such as Farmer Field Schools (FFS) and Participatory Rural Appraisal (PRA), allow farmers to co-develop and test climate-resilient technologies, ensuring their relevance and adaptability (Paparrizos *et.al.,* 2021). One of the key contributions of participatory extension to CSA is the promotion of climate-resilient crop varieties and diversified cropping systems. Participatory plant breeding (PPB) has enabled farmers to select and develop crop varieties that exhibit drought tolerance, flood resistance, and improved nutrient use efficiency. Participatory extension has facilitated the adoption of climate-adaptive soil and water conservation techniques, such as agroforestry, contour farming, and rainwater harvesting, by encouraging farmer-led experimentation and peer-to-peer learning. Participatory extension models have supported the dissemination of climate information services, empowering farmers to make informed decisions regarding planting dates, water management, and pest control under changing climatic conditions. Mobile-based participatory platforms and community weather monitoring networks have significantly enhanced access to localized climate data, leading to improved climate risk management (Caine *et.al.,* 2015). The success of participatory approaches in CSA adoption demonstrates that sustainable farming practices are most effective when farmers actively engage in knowledge generation, technology development, and adaptation processes.

**B. Sustainable Soil and Water Management Through Collective Action**

Sustainable soil and water management (SSWM) is essential for ensuring long-term agricultural productivity, maintaining ecosystem health, and mitigating climate change impacts. Participatory extension has facilitated the adoption of sustainable soil and water management practices through collective action, farmer-led experimentation, and knowledge-sharing networks. Unlike conventional extension approaches that prescribe standardized soil and water conservation techniques, participatory models emphasize localized solutions tailored to specific agroecological conditions. Participatory watershed management programs have been particularly effective in promoting soil conservation and water resource management in arid and semi-arid regions. These initiatives engage local communities in land-use planning, erosion control, and integrated water resource management, leading to improved soil fertility, enhanced groundwater recharge, and reduced land degradation. Community-driven terracing, contour farming, and mulching techniques have been widely adopted through participatory learning processes, ensuring their long-term sustainability (Meetei *et.al.,* 2024). Participatory extension has encouraged the adoption of organic soil fertility management strategies, such as composting, green manure application, and crop residue retention. By integrating farmer knowledge with scientific recommendations, participatory approaches have facilitated the transition toward regenerative agriculture, reducing dependency on synthetic fertilizers and enhancing soil microbiome health. The collective action fostered by participatory extension models has proven instrumental in scaling up sustainable soil and water management practices, strengthening the resilience of farming communities in the face of environmental challenges.

**6. Case Studies of Successful Participatory Agricultural Extension Models**

**A. Farmer-Led Extension Programs in Different Agroecological Zones**

Farmer-led extension programs have emerged as a powerful alternative to conventional top-down extension models, fostering peer-to-peer learning and localized innovation across diverse agroecological zones. These programs empower farmers to act as knowledge facilitators, leveraging their experiential learning to disseminate best practices and adaptive strategies within their communities (Osumba *et.al.,* 2021). The success of farmer-led extension models has been documented in multiple regions, particularly in Sub-Saharan Africa, Asia, and Latin America, where resource constraints have limited the effectiveness of traditional extension services. In East Africa, the Farmer Trainers Approach has been widely adopted, where experienced farmers are selected to conduct training sessions, facilitate on-farm experiments, and support their peers in implementing improved agricultural practices. In India, the Self-Employed Women’s Association (SEWA) has implemented farmer-to-farmer learning programs that enable women farmers to share knowledge on sustainable agriculture, agroecology, and market linkages. Research has shown that farmer-led extension programs enhance knowledge retention, increase technology adoption rates, and foster community resilience by strengthening local agricultural innovation systems (Ensor *et.al.,* 2022). These programs demonstrate that sustainable agricultural transformation is most effective when farmers are at the centre of extension and advisory service delivery.

**B. Participatory Technology Development (PTD) in Resource-Poor Farming Systems**

Participatory Technology Development (PTD) has been instrumental in addressing the challenges faced by resource-poor farmers, enabling them to co-develop, test, and adapt technologies that align with their socio-economic and agroecological contexts. Unlike conventional research models that often impose externally developed solutions, PTD fosters collaborative innovation processes that integrate farmer knowledge, local biodiversity, and scientific research. A notable example of PTD is the participatory varietal selection (PVS) approach, where farmers engage in the selection of crop varieties that best suit their needs in terms of yield stability, drought tolerance, pest resistance, and market preferences. In West Africa, PTD initiatives focusing on millet and sorghum improvement have resulted in the widespread adoption of resilient crop varieties, reducing food insecurity and enhancing climate adaptation (Azevedo *et.al.,* 2019). PTD has also been applied in livestock management, where pastoralist communities in Ethiopia and Kenya have co-developed strategies for rangeland rehabilitation, disease control, and water harvesting, improving the sustainability of livestock-based livelihoods. The success of PTD in resource-poor farming systems underscores the importance of participatory research in fostering locally adapted, farmer-driven technological innovations.

**C. Role of Community-Based Organizations (CBOs) and Cooperatives in Agricultural Extension**

Community-Based Organizations (CBOs) and cooperatives have played a significant role in participatory agricultural extension by facilitating collective action, resource mobilization, and farmer-led decision-making. These organizations provide platforms for farmers to access training, financial services, and input supply networks, enhancing their capacity to implement sustainable farming practices. One of the most successful models of CBO-driven extension is found in Kenya’s dairy sector, where cooperative societies have established extension support systems that provide training on fodder management, artificial insemination, and dairy hygiene practices. In Latin America, participatory coffee cooperatives have empowered smallholder farmers to adopt organic farming practices, gain certification, and access premium markets (Sirdey *et.al.,* 2020).

**D. Participatory Approaches in Precision Agriculture and Smart Farming**

The integration of participatory extension with precision agriculture and smart farming technologies has opened new avenues for sustainable agricultural development. Participatory approaches ensure that digital innovations, such as remote sensing, GIS mapping, and sensor-based irrigation systems, are adapted to the needs and capacities of smallholder farmers. A case study from India’s Andhra Pradesh region highlights the successful implementation of participatory digital extension, where farmers use mobile applications to access weather forecasts, soil health data, and pest surveillance information. In Brazil, participatory precision agriculture initiatives have enabled farmers to optimize fertilizer application and irrigation scheduling, reducing environmental footprints while enhancing productivity (Lakhiar *et.al.,* 2024).

**7. Challenges in Implementing Participatory Approaches in Agricultural Extension**

**A. Institutional Barriers and Policy Constraints**

Institutional barriers and policy constraints significantly affect the successful implementation of participatory agricultural extension approaches. Many national agricultural extension systems are still structured around traditional top-down models that prioritize centralized decision-making, rigid bureaucratic processes, and hierarchical knowledge dissemination. These institutional frameworks often fail to accommodate the flexible, decentralized, and farmer-driven methodologies that characterize participatory extension. In many developing countries, extension policies continue to emphasize production-oriented targets rather than farmer engagement and capacity building, limiting the scope for participatory innovations. One of the primary institutional challenges is the lack of coherent policies supporting participatory extension. Many agricultural development policies remain focused on standardized, large-scale technology transfer programs, overlooking the diverse needs and socio-ecological conditions of smallholder farmers. Institutional resistance to participatory approaches arises due to entrenched power dynamics between extension agents, researchers, and farmers, with experts often reluctant to relinquish control over the knowledge-generation process (Felt *et.al.,* 2007). Policy fragmentation and weak intersectoral coordination further exacerbate implementation challenges. Effective participatory extension requires collaboration between agricultural departments, research institutions, farmer organizations, and private-sector actors. In many cases, these stakeholders operate in isolation due to conflicting mandates, poor information-sharing mechanisms, and limited policy integration. Decentralization of extension services, while theoretically supportive of participatory approaches, has also faced challenges where local governments lack the technical expertise, financial resources, and institutional capacity to effectively implement farmer-led extension models.

**B. Socio-Cultural and Economic Challenges Affecting Participation**

Socio-cultural and economic factors play a crucial role in determining the success of participatory agricultural extension programs. Cultural norms, power dynamics, and historical farming practices shape how farmers interact with extension services and adopt new technologies. In many rural societies, knowledge-sharing structures are deeply rooted in traditional social hierarchies, which can hinder equitable participation in extension initiatives (Qureshi *et.al.,* 2018). In patriarchal communities, women farmers often face systemic barriers to participation, as agricultural knowledge exchange is predominantly male-dominated. Another key socio-cultural challenge is farmers' trust in external interventions. Many smallholder farmers have historically been subjected to failed extension programs that promoted unsuitable or unsustainable agricultural technologies. As a result, skepticism towards new participatory extension initiatives can limit engagement, particularly if farmers perceive them as externally driven rather than community-led. Economic factors also constrain participation in agricultural extension. Smallholder farmers, particularly those in resource-poor settings, often struggle with financial instability, limited access to credit, and market uncertainties, making it difficult for them to invest time and resources in participatory initiatives. In cases where participatory programs require farmers to co-finance extension services or contribute labour for group activities, economic hardships can reduce participation levels, particularly among marginalized groups (Prain *et.al.,* 2020).

**C. Resource Limitations and Funding Issues in Participatory Extension Models**

Funding constraints pose a significant challenge to the sustainability of participatory agricultural extension models. Unlike conventional extension services that often rely on government subsidies, participatory approaches require long-term investment in capacity building, facilitation, and monitoring to ensure meaningful farmer engagement. Many governments and development agencies operate under short-term funding cycles, leading to discontinuity in participatory extension programs. One of the critical issues is the misalignment of donor priorities with farmer needs. International funding agencies often emphasize measurable short-term impacts, such as yield increases or technology adoption rates, rather than long-term participatory processes that enhance farmer knowledge and empowerment. As a result, many participatory programs struggle to secure sustained financial support, leading to inconsistent implementation and withdrawal of key services over time (Mansuri *et.al.,* 2012). Resource limitations are also evident in infrastructure and logistical challenges. Many rural areas lack the necessary facilities, transportation networks, and communication infrastructure to support participatory learning platforms such as Farmer Field Schools (FFS) and community-based extension groups. The high transaction costs associated with participatory extension such as hiring trained facilitators, organizing workshops, and conducting field-based research often exceed the financial capacities of national extension agencies and local farmer organizations.

**D. Gaps in Capacity Building and Training of Extension Workers in Participatory Methods**

The successful implementation of participatory agricultural extension hinges on the skills, attitudes, and competencies of extension agents. Many extension workers have been trained primarily in conventional top-down extension methodologies, limiting their ability to facilitate farmer-led learning processes. The transition from expert-driven knowledge dissemination to participatory facilitation requires a fundamental shift in extension worker roles, emphasizing dialogue, co-learning, and social mediation (Voinov *et.al.,* 2016). One of the major gaps in capacity building is the inadequate integration of participatory extension methodologies into agricultural education curricula. Many agricultural universities and training institutions continue to emphasize technical skills over participatory facilitation techniques, leaving extension agents ill-equipped to engage farmers effectively. Many national extension services lack structured in-service training programs that provide continuous professional development in participatory approaches. Extension workers often face logistical constraints such as high farmer-to-extension agent ratios, lack of transport, and administrative burdens that limit their ability to conduct participatory field activities. These challenges highlight the need for comprehensive capacity-building programs that equip extension agents with participatory research skills, facilitation techniques, and community engagement strategies.

**E. Resistance to Change and Adoption of New Technologies by Farmers**

Resistance to change among farmers presents another key challenge in implementing participatory extension (Nettle *et.al.,* 2022). Farmers' willingness to adopt new practices and technologies is influenced by several factors, including risk perceptions, cultural attachment to traditional farming methods, and past experiences with extension services. In many cases, participatory extension initiatives introduce unfamiliar concepts, such as conservation agriculture, integrated pest management (IPM), or digital farming technologies, which may require behavioral shifts that farmers are hesitant to undertake. Psychological and social factors also play a role in resistance to change. Many rural communities rely on established social networks for knowledge exchange, meaning that individual adoption decisions are influenced by group norms and community validation (Chow *et.al.,* 2008). If participatory extension programs do not align with local social structures or fail to gain community-wide acceptance, adoption rates can remain low despite program implementation. The perceived economic risks associated with adopting new agricultural practices can deter farmer participation. Farmers who rely on subsistence agriculture or operate within volatile market conditions may be reluctant to experiment with new technologies due to concerns about potential yield losses, input costs, or labour requirements. This underscores the importance of integrating risk mitigation strategies, such as adaptive on-farm trials, participatory financial support mechanisms, and peer mentoring, within participatory extension frameworks.

**8. Strategies for Strengthening Participatory Approaches in Agricultural Extension**

**A. Policy Interventions to Promote Participatory Agricultural Extension**

Effective policy interventions are essential for mainstreaming participatory approaches in agricultural extension and ensuring their long-term sustainability. Many agricultural extension systems remain rooted in top-down models that prioritize centralized decision-making and linear knowledge transfer, limiting opportunities for farmer-driven engagement (Mapiye *et.al.,* 2024). Governments and international organizations must implement policy frameworks that institutionalize participatory extension by integrating it into national agricultural development strategies, research programs, and rural advisory services. Decentralization policies have been recognized as a key mechanism for strengthening participatory extension. By shifting decision-making authority from national governments to local institutions, decentralization fosters context-specific extension solutions that reflect farmers’ needs and priorities. Effective decentralization requires complementary policies that build the capacity of local governments, extension agents, and farmer organizations to manage participatory programs effectively. Financial policies that ensure sustained funding for participatory extension initiatives are equally crucial. Governments must allocate dedicated budgets for farmer-led extension programs, participatory research initiatives, and knowledge-sharing platforms to reduce dependence on short-term donor funding (Agwu *et.al.,* 2023). Policies that incentivize farmer participation, such as subsidies for community-managed extension services, can enhance farmer engagement and knowledge co-creation.

**B. Strengthening Public-Private Partnerships (PPP) in Extension Services**

Public-private partnerships (PPPs) have emerged as a viable strategy for enhancing participatory extension by leveraging the strengths of both public institutions and private sector actors. Government extension services often lack the financial resources and technical expertise required for large-scale participatory initiatives, whereas private agribusinesses, input suppliers, and non-governmental organizations (NGOs) can provide complementary support through training programs, market linkages, and technology dissemination. Successful PPP models in participatory extension have been documented in various regions. In India, the e-Choupal initiative by ITC Limited has integrated participatory knowledge-sharing mechanisms into its digital advisory services, enabling smallholder farmers to access real-time market information, weather updates, and agronomic recommendations (Khare *et.al.,* 2011). In sub-Saharan Africa, partnerships between multinational seed companies and farmer cooperatives have facilitated participatory varietal selection, ensuring that newly developed crop varieties align with farmers’ preferences and environmental conditions. For PPPs to be effective, regulatory frameworks must ensure that private sector participation does not lead to the commercialization of extension services at the expense of smallholder farmers. Governments must establish mechanisms that balance profit-driven interests with the principles of inclusivity, accessibility, and sustainability in participatory extension models.

**C. Capacity Development of Extension Agents and Farmer Leaders**

The transition to participatory extension requires substantial investment in the capacity development of extension agents and farmer leaders. Many extension professionals are trained primarily in conventional knowledge transfer methods, with limited exposure to participatory facilitation techniques (Lukuyu *et.al.,* 2012). Training programs must therefore be reoriented to equip extension personnel with skills in group facilitation, participatory learning methodologies, and social mobilization. Capacity development efforts must also target farmer leaders, who play a crucial role in knowledge dissemination within their communities. Farmer-led training-of-trainers (TOT) programs have been widely successful in strengthening participatory extension, as seen in the widespread adoption of Farmer Field Schools (FFS) across Africa and Asia. Mentoring networks that pair experienced farmers with extension workers can enhance mutual learning and promote farmer-led innovations.

**D. Leveraging Digital Technologies for Participatory Knowledge Dissemination**

The rapid expansion of digital technologies has transformed agricultural extension, offering new opportunities for participatory knowledge-sharing and decision-making. Mobile-based advisory platforms, participatory mapping tools, and social media networks enable real-time farmer-to-farmer learning, reducing geographic and logistical barriers to extension access (Naika *et.al.,* 2021). Participatory video and community radio programs have also proven effective in capturing and disseminating farmer-generated knowledge, particularly in remote rural areas. Digital participatory tools such as crowdsourced data collection platforms allow farmers to contribute field-level insights on climate conditions, pest outbreaks, and soil health, enhancing collective decision-making processes.

**E. Enhancing Multi-Stakeholder Collaboration in Extension Services**

Participatory agricultural extension thrives in environments where multiple stakeholders—including farmers, researchers, policymakers, NGOs, and private sector actors—collaborate to co-develop and implement knowledge-sharing initiatives. Multi-stakeholder innovation platforms (MSIPs) have gained traction as effective mechanisms for fostering dialogue, consensus-building, and joint problem-solving in extension services. Successful examples of multi-stakeholder collaboration include participatory research alliances, community-driven extension networks, and intersectoral task forces focused on sustainable agriculture (Barletti *et.al.,* 2020). These platforms enable farmers to actively engage in policy dialogues, ensuring that extension services remain responsive to their needs and priorities.

**9. Future and Emerging Trends in Participatory Agricultural Extension**

Artificial intelligence (AI) and big data analytics are revolutionizing participatory agricultural extension by enhancing real-time decision-making, predictive modeling, and personalized advisory services. AI-powered chatbots and digital assistants provide farmers with interactive, voice-based advisory services in multiple languages, bridging literacy and accessibility gaps. Big data applications in participatory extension include climate forecasting, precision agriculture, and digital farmer profiling, enabling data-driven participatory research and community-based decision-making. Ethical concerns regarding data ownership, privacy, and digital inclusivity must be addressed to ensure that AI-driven participatory extension remains equitable and farmer-centered (Jamba *et.al.,* 2024). Future participatory extension models will place greater emphasis on farmer-led innovation networks, where farmers collectively experiment with, adapt, and scale up sustainable agricultural practices. These networks leverage peer-to-peer learning and grassroots knowledge exchange to enhance resilience, particularly in climate-vulnerable regions. Participatory extension will increasingly focus on climate resilience by integrating locally adapted climate-smart technologies, community-led disaster risk reduction strategies, and participatory climate forecasting tools. This shift is particularly critical for smallholder farmers facing escalating climate variability and extreme weather events. Participatory agroforestry extension models will gain prominence as sustainable land management strategies, emphasizing farmer-led tree-planting programs, participatory biodiversity conservation, and regenerative agroecology practices (Isaac *et.al.,* 2024). These models align with global efforts to combat deforestation, land degradation, and biodiversity loss.

**Conclusion**

participatory approaches in agricultural extension have emerged as transformative models for enhancing knowledge exchange, technology adoption, and sustainable farming practices. By placing farmers at the centre of the learning process, these approaches bridge the gap between scientific research and local knowledge, fostering more resilient and context-specific agricultural solutions. Despite challenges such as institutional constraints, funding limitations, and socio-cultural barriers, strategies including policy reforms, capacity building, public-private partnerships, and digital innovations have strengthened participatory extension frameworks. The integration of emerging technologies such as artificial intelligence, big data, and precision agriculture further enhances participatory decision-making and climate adaptation. Looking ahead, expanding participatory approaches beyond production to market linkages, value chain development, and agroforestry will ensure greater farmer empowerment and food security. A sustained commitment from policymakers, researchers, and farming communities is essential to scale participatory extension and drive inclusive agricultural transformation globally.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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