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RETHINKING AGRICULTURAL EXTENSION FOR SUSTAINABLE AGRICULTURE: BUILDING COLLABORATIVE KNOWLEDGE SYSTEMS

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ABSTRACT

Sustainable agriculture depends not only on the availability of improved technologies but also on whether farmers can interpret, test, adapt and sustain them under specific ecological and livelihood conditions. Conventional agricultural extension has often treated this challenge as a problem of information delivery: researchers generate recommendations, extension agents communicate them, and farmers are expected to adopt them. This critical narrative review examines why that model is insufficient for sustainability-oriented change and how extension can be reoriented towards knowledge co-production. Drawing on literature on agricultural innovation systems, participatory extension, farmer learning, digital agriculture and collaborative governance, the review develops three arguments. First, farmers require combinations of scientific, experiential, local, market and climate knowledge rather than isolated technical messages. Second, adoption is a negotiated and reversible process shaped by risk, affordability, compatibility, trust, social position and opportunities for local experimentation. Third, extension contributes most effectively when it brokers relationships among farmers, researchers, public institutions, civil society, and market actors rather than functioning solely as a delivery channel. Participatory approaches such as Farmer Field Schools and farmer-to-farmer learning can strengthen relevance and ownership, while digital tools can extend reach but cannot replace trusted human interpretation. The review concludes that extension performance should be assessed through adaptive capacity, sustained practice, inclusion, resource stewardship and institutional learning, not merely through numbers trained or technologies disseminated. A practical agenda is proposed for farmer-centred, blended and accountable agricultural knowledge systems.

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INTRODUCTION

Agriculture is expected to increase and stabilise food production while responding to climate change, biodiversity loss, soil degradation, water scarcity and persistent rural inequality. These pressures make sustainable agriculture more than a technical objective. It is a process of balancing productivity, ecological integrity, livelihood security and social justice under conditions of uncertainty (Pretty, 2008; IPCC, 2022; FAO, 2023). New varieties, climate information, soil-management practices and digital tools remain essential, but their availability does not ensure their use. Many technically credible innovations are only partly adopted, adapted in unanticipated ways, abandoned after initial trials or rejected altogether. The central problem is therefore not simply how to generate more knowledge, but how to make knowledge relevant, trusted, feasible and actionable within diverse farming systems.

Agricultural extension has historically addressed this problem through a linear sequence: research institutions develop technologies, extension organisations translate recommendations and farmers adopt them. This arrangement supported major gains in agricultural productivity and remains useful when information is stable, urgent and broadly applicable, as with a pest alert or a clearly defined animal-health protocol. Its limitations become more visible when problems involve trade-offs, uncertainty and local variation. Practices such as integrated pest management, climate adaptation, soil restoration, water conservation and agroecological diversification require farmers to combine general evidence with farm-specific observation, household resources and collective arrangements (Sinclair et al., 2019). A technically sound recommendation may be unusable when it requires unavailable labour, exposes the household to unacceptable risk, conflicts with tenancy arrangements or lacks a viable market.

This gap between knowledge and practice is often described as a science-policy-practice problem. Effective knowledge systems must produce scientifically credible information, salient to users and legitimate in the eyes of those affected (Cash et al., 2003). These conditions are difficult to achieve through one-way communication. They depend on interaction among actors who hold different forms of knowledge and different kinds of authority. Farmers contribute experience of soils, rainfall, pests, labour and markets; researchers contribute analytical methods and comparative evidence; extension professionals translate and connect; public institutions shape incentives and infrastructure; and community organisations create the social conditions for collective learning.

The concept of knowledge co-production captures this shift. It refers to processes in which academic and non-academic actors jointly frame problems, generate evidence, assess options and interpret results. In sustainability research, robust co-production is context-based, pluralistic, goal-oriented and interactive (Norström et al., 2020). Applied to agricultural extension, it does not mean that all forms of knowledge are equally reliable in every circumstance, nor that scientific expertise becomes unnecessary. Rather, it means that evidence is more likely to guide sustainable action when it is tested against local realities and when farmers have meaningful influence over problem definition and adaptation.

This article provides a focused critical review of that transition. It asks three questions: why are conventional transfer models inadequate for sustainability-oriented extension; how do farmers evaluate and adapt agricultural knowledge; and what institutional changes are required for extension to support co-production? The review deliberately avoids treating every component of agricultural innovation as a separate topic. Instead, community engagement, digital advisory services and multi-actor governance are examined only insofar as they strengthen or weaken the movement from information delivery to sustained, locally appropriate practice.

Review Scope and Analytical Approach

The article adopts a critical narrative review approach. It synthesises foundational and recent literature on agricultural extension, agricultural innovation systems, participatory learning, knowledge co-production and digital agriculture. Seminal works are retained where they define concepts that continue to structure the field, while recent literature and institutional reports are used to examine contemporary sustainability, inclusion and digitalisation challenges. The analysis is organised around a simple pathway: knowledge generation, communication, farmer interpretation, local experimentation, sustained practice and feedback to research and policy.

The review is analytical rather than exhaustive. Its purpose is not to catalogue all extension methods or technologies, but to identify the conditions under which knowledge becomes usable and durable. Evidence is interpreted through four criteria: relevance to farmers' decisions, opportunities for adaptation, distribution of voice and authority, and contribution to sustainability outcomes. This framework also helps distinguish co-production from consultation. A programme may consult farmers while preserving external control over objectives, methods and evaluation. Co-production requires a stronger influence over what problem is addressed, how options are tested and how success is defined (Turnhout et al., 2020).

Why Traditional Extension Models are Insufficient?

The conventional transfer model assumes a relatively clear boundary between knowledge producers and knowledge users. Research organisations are positioned as the origin of valid knowledge, extension agents as intermediaries and farmers as recipients. The model is administratively attractive because responsibilities are visible and performance can be measured through messages delivered, demonstrations conducted or technologies adopted. Diffusion theory added an important social dimension by showing that adoption depends on communication channels, time, social systems and perceived attributes of innovations (Rogers, 2003). Nevertheless, the adoption orientation often leaves the technology itself insufficiently questioned. When farmers reject a recommendation, the explanation can default to poor awareness or conservatism rather than a rational assessment of risk and fit.

Sustainable agriculture exposes this weakness because it rarely involves a single, standardised technology. Conservation agriculture, integrated nutrient management, agroforestry and climate-smart practices are bundles of decisions whose effects depend on soil, water, labour, livestock, market access and institutional support. The same practice may reduce risk for one household and increase it for another. Extension therefore cannot assume that a recommendation travels unchanged from research to farm. It must support translation and adaptation.

Systems approaches emerged in response to these limitations. Agricultural Knowledge and Information Systems and Agricultural Innovation Systems understand innovation as the outcome of relationships among farmers, research organisations, advisory services, government agencies, firms and civil society (World Bank, 2012; Klerkx et al., 2012). The focus shifts from the supply of technology to a network's capacity to learn and solve problems. Innovation brokers and boundary organisations become important because actors differ in language, incentives and resources (Klerkx and Leeuwis, 2009). An extension agent may therefore need to connect a farmer group with a researcher, financial service, input supplier or local authority rather than simply explain a recommendation.

Knowledge co-production takes this systems perspective further by redistributing epistemic authority. Farmers are recognised not merely as adopters but as observers and experimenters. Their knowledge is often tacit and situated: it is embedded in repeated practice and may be difficult to express in formal categories. Scientific knowledge, by contrast, offers measurement, comparison and causal explanation. Neither is sufficient alone. Scientific evidence can lack contextual fit, while local knowledge can be incomplete, unevenly distributed or poorly suited to rapidly changing conditions. Co-production is valuable because it creates structured opportunities to compare, test and refine different claims. The transition is illustrated in Figure 1. The stages should not be read as a simple historical replacement. Linear communication remains appropriate for some tasks, and many extension systems combine all three approaches. The practical question is whether the institutional arrangement matches the problem. The more uncertain, contested and context-dependent the problem, the stronger the need for feedback, experimentation and shared interpretation.

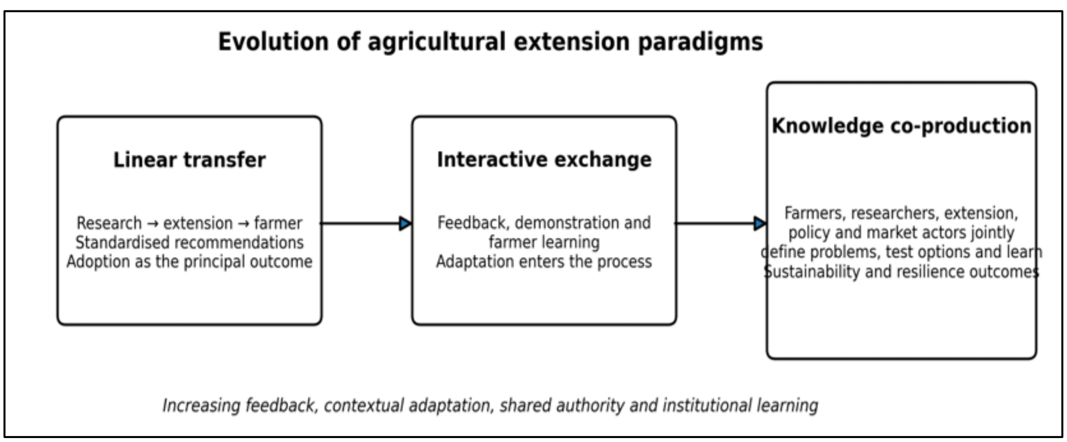

Figure 1. Evolution from linear knowledge transfer to knowledge co-production in agricultural extension.

How Farmers Interpret, Adopt and Sustain Knowledge

Knowledge availability represents only the starting point of behavioural change. Farmers evaluate recommendations in relation to expected benefits, perceived risks, financial requirements, labour demands, compatibility with existing practices, and the credibility of the information source. Adoption decisions are therefore not simply a consequence of receiving technically valid information but emerge from complex interactions among economic, social, institutional, and environmental factors. For smallholder farmers, these decisions are particularly significant because failed investments may directly threaten household food security, income stability, or debt repayment capacity. Consequently, what may appear to external observers as resistance to innovation often represents a rational response to uncertainty and constrained resources (Feder et al., 1985; Rogers, 2003; Pannell et al., 2006).

Economic feasibility frequently determines whether farmers can translate knowledge into practice. A technology may provide long-term environmental benefits while requiring substantial short-term investments, additional labour, or temporary reductions in income during transition periods. Without access to credit, insurance mechanisms, secure land tenure, or reliable markets, farmers may be unable to adopt practices even when they recognise their potential value. Social inequalities also shape adoption decisions: tenant farmers may hesitate to invest in improvements with delayed benefits, women may face restricted access to land and financial resources, and young farmers may possess digital capabilities while lacking productive assets. Therefore, extension approaches that focus solely on information delivery risk increasing awareness without addressing the structural conditions that enable or constrain practice change (Feder et al., 1985; Doss, 2006; Glover et al., 2019).

Compatibility and trialability are additional factors influencing innovation uptake. Farmers are more likely to engage with new practices when innovations can be tested on a limited scale, compared with existing methods, and modified without excessive financial risk. Rogers' diffusion framework identifies relative advantage, compatibility, complexity, trialability, and observability as key attributes affecting adoption decisions (Rogers, 2003). Demonstration plots can support learning when they provide locally relevant evidence; however, their influence decreases when demonstrations operate under conditions that farmers cannot realistically reproduce. Participatory trials are often more effective because farmers contribute to selecting treatments, interpreting results, and evaluating trade-offs. Such approaches generate not only greater acceptance but also improved understanding of where, when, and for whom specific innovations are appropriate (Pretty, 1995; Hauser et al., 2016).

Trust strongly influences how farmers interpret and respond to agricultural knowledge. Farmers evaluate not only the content of recommendations but also the credibility of the institution and individuals providing advice. Information may be discounted when extension services provide limited follow-up, when private advisory systems have undisclosed commercial interests, or when previous interventions have extracted knowledge or data without delivering meaningful benefits. Trust develops through repeated interaction, transparency, responsiveness, and demonstrated competence. This helps explain why farmer-to-farmer learning can be highly influential, as peers often share similar constraints and provide observable evidence of innovation performance under comparable conditions. However, peer-learning systems may also reproduce existing inequalities when farmer representatives are selected from socially advantaged groups without attention to gender, wealth, or social inclusion (Conley & Udry, 2010; Spielman et al., 2011; Klerkx & Proctor, 2013).

Adoption should therefore not be viewed as an outcome but as an evolving learning process. Farmers frequently modify technologies, combine innovations with existing practices, temporarily discontinue use after disappointing results, or abandon practices when subsidies, markets, or project support disappear. Sustained practice change depends on continued access to inputs, technical support, repair services, finance, and social networks. Extension evaluation should consequently distinguish between awareness, initial trial, adaptation, continued use, and long-term institutionalisation of practices. Measuring only the number of initial adopters can overestimate programme effectiveness when longer-term sustainability is not assessed (Rogers, 2003; Douthwaite et al., 2009; Klerkx et al., 2012).

Sustainability outcomes frequently require collective rather than individual action. Practices related to water management, grazing systems, pest surveillance, biodiversity conservation, and landscape restoration depend on coordination among farmers, communities, and institutions. In such contexts, extension must support not only individual knowledge acquisition but also collective learning, negotiation, rule formation, and shared monitoring. Research on social-ecological systems demonstrates that durable resource management depends on institutional arrangements that promote participation, accountability, and local adaptation rather than information availability alone (Ostrom, 2009; Meinzen-Dick et al., 2018).

Community Engagement as a Mechanism of Co-production

Community engagement adds value when it changes the quality of learning and decision-making. Informing communities, consulting them and involving them in implementation are not equivalent to sharing authority.

Participatory language can conceal highly predetermined programmes. The critical distinction is whether farmers can influence the questions, options and criteria by which outcomes are judged.

Farmer Field Schools provide one of the clearest examples of learning-oriented extension. Farmers meet through a production cycle, observe field conditions, conduct comparisons and interpret results with a facilitator. The approach can strengthen ecological understanding, confidence and collective problem-solving rather than simply transmit a package. Reviews report benefits across human, social, natural and financial domains, although outcomes depend heavily on facilitator quality, local ownership and long-term institutional support (van den Berg et al., 2020). Social capital can mediate these effects by enabling participants to exchange knowledge and act collectively (Charatsari et al., 2020). Farmer-to-farmer extension, co-design and innovation platforms extend the same principle. Farmer-to-farmer approaches use trusted social networks; co-design brings users into the development of tools or practices; and innovation platforms assemble actors who control different resources. Their value lies in shortening feedback loops. Researchers learn why a recommendation fails, extension organisations identify service gaps, policymakers encounter implementation constraints and farmers gain access to wider expertise.

These approaches also have limits. Participation is costly in time and can create fatigue when communities are repeatedly invited to meetings without influence or benefit. Local elites may dominate discussion. Women, tenants, landless workers and remote communities may be formally represented but practically excluded by meeting times, language, mobility or social norms. Co-production therefore requires explicit safeguards: transparent participant selection, skilled facilitation, accessible communication, compensation for substantial time commitments and mechanisms for disagreement and appeal.

Indigenous and local knowledge requires particular care. It should not be romanticised as inherently sustainable, nor extracted as free data for external research. Ethical integration requires recognition of collective ownership, informed consent, attribution and benefit sharing. The objective is respectful comparison and joint learning, especially where long-term ecological observation can complement scientific monitoring.

Digital Advisory Services: Extension or Substitution?

Digital tools have expanded the speed and reach of agricultural communication. Mobile messaging, remote sensing, decision-support systems and artificial intelligence can provide weather forecasts, pest alerts, market information and increasingly personalised recommendations. They can also reduce the cost of contacting dispersed farmers and create new channels for feedback. OECD (2021) and FAO (2022) emphasise the potential of digitalisation and automation to improve agricultural decision-making and policy. Their value, however, is often overstated when digital delivery is treated as a substitute for extension. Data and recommendations still require interpretation. A forecast is useful only when it is timely, localised and linked to feasible actions. A crop-disease diagnosis is risky when image quality is poor, the model was trained in different agroecological conditions or the recommended product is unavailable. Digital agriculture therefore raises the same knowledge problem in a new form: relevance cannot be assumed from technical sophistication. Digital exclusion is equally important. Access depends on connectivity, device ownership, affordability, literacy, language and confidence. Gendered access to phones and data can reproduce existing inequalities. Digital platforms may also create new dependencies when farmers cannot inspect algorithms, transfer their records or control how farm data are used. Research on Agriculture 4.0 consequently calls for responsible innovation that works for people and the planet rather than technology-led transformation alone (Rose et al., 2021).

A blended model is more defensible. Digital systems can handle routine information, expand surveillance, and support record-keeping, while extension professionals and farmer networks provide interpretation, verification, and adaptation. Human oversight is particularly important for high-consequence advice concerning pesticide use, livestock health, irrigation or credit. The future role of extension is therefore not displaced by digitalisation; it becomes more demanding. Professionals need capacities in data literacy, facilitation, risk communication and ethical governance in addition to technical agriculture.

Building Accountable Agricultural Knowledge Ecosystems

Knowledge co-production requires institutional arrangements capable of sustaining relationships beyond individual projects and temporary interventions. Farmers, researchers, extension agencies, governments, civil-society organisations, and private firms contribute different forms of knowledge, resources, and expertise; however, their objectives, incentives, and capacities are not always aligned. Although multi-actor collaboration can strengthen agricultural innovation by combining diverse perspectives and capabilities, it may also reproduce existing power asymmetries when certain actors control funding, technical expertise, data infrastructures, or decision-making processes. Therefore, governance is not an additional component of knowledge co-production but a central condition determining whose knowledge is recognised, how decisions are made, and whether innovation processes remain inclusive (Klerkx et al., 2012; Turnhout et al., 2020).

Extension organisations are particularly well positioned to function as knowledge brokers because they connect farmers' experiential knowledge with scientific institutions, policy systems, and innovation networks. However, fulfilling this role requires institutional capacity, including stable financing, manageable workloads, and professional development in facilitation, partnership building, conflict management, and participatory evaluation. Contemporary extension systems increasingly require professionals who act not only as information providers but also as facilitators of learning, coordination, and innovation processes. Consequently, extension performance assessment should move beyond numerical indicators such as the number of farm visits or demonstrations and incorporate measures of responsiveness, learning outcomes, farmer engagement, and adaptive capacity (Klerkx and Leeuwis, 2009; Davis and Sulaiman, 2014).

Research institutions also require changes in incentive structures to support meaningful engagement with farming communities. Conventional academic systems often prioritise peer-reviewed publications and disciplinary outputs, which can discourage long-term collaboration with farmers and non-academic stakeholders. Transdisciplinary research approaches emphasise that practical relevance and societal impact should complement scientific excellence by involving knowledge users throughout the research process, including problem definition, experimentation, interpretation, and application of findings (Lang et al., 2012; Norström et al., 2020).

Governments have a distinct responsibility in sustaining agricultural knowledge ecosystems by providing public goods and addressing inequalities in access to knowledge and advisory services. This includes supporting extension infrastructure in underserved regions, strengthening farmer organisations, maintaining open access to climate and environmental information, establishing quality standards for advisory services, and developing appropriate data governance frameworks. While pluralistic advisory systems involving public, private, and civil-society providers can increase diversity and responsiveness, inadequate coordination may create fragmented services, inconsistent recommendations, and unequal access among farmers (Birner et al., 2009; Labarthe and Laurent, 2013).

Private-sector participation can contribute significantly to agricultural innovation through the provision of technologies, financial services, logistics, and market connections. However, commercial involvement also introduces potential conflicts when advisory services become closely linked with product promotion or when digital platforms rely on extracting and controlling farmer-generated data. Responsible private-sector engagement therefore requires transparency, farmer consent, data protection, and mechanisms that ensure commercial interests do not undermine sustainability objectives or farmer autonomy (Bronson and Knezevic, 2016; Klerkx et al., 2019).

Farmer organisations and cooperatives represent another critical component of accountable knowledge ecosystems because they transform individual experiences into collective knowledge and political representation. These organisations can facilitate experimentation, negotiate advisory services, and provide platforms through which farmers participate in research and policy processes. However, their contribution depends on internal accountability, inclusive representation, and meaningful participation of women, youth, and marginalised groups. Knowledge ecosystems can only achieve inclusiveness when the institutions through which participation occurs are themselves equitable and representative (Fischer and Qaim, 2012; Klerkx and Begemann, 2020).

A fundamental governance principle therefore follows: every actor involved in knowledge co-production should be accountable not only for the resources they contribute but also for how they respond to feedback and share decision-making authority. Researchers should demonstrate how farmer knowledge influences research priorities; extension organisations should document adaptation and follow-up; digital providers should ensure transparency regarding data practices; and policymakers should incorporate implementation evidence into policy revision. Without these reciprocal accountability mechanisms, knowledge co-production risks becoming a symbolic form of participation that changes terminology while leaving underlying power structures unchanged (Cooke and Kothari, 2001; Turnhout et al., 2020).

Implications for Extension Policy and Practice

The The review suggests a concise reform agenda for repositioning agricultural extension as a driver of sustainable transformation. First, extension mandates should move beyond technology delivery toward problem-solving, facilitation, and innovation brokerage. Although technical expertise remains fundamental, contemporary extension professionals require additional competencies in diagnosis, communication, facilitation, negotiation, partnership building, and adaptive management. Extension agents should be empowered to modify programmes according to local social, ecological, and economic contexts rather than merely implementing centrally designed interventions (Rivera and Sulaiman, 2009; Davis and Sulaiman, 2014; Klerkx and Leeuwis, 2009).

Second, farmer participation should be institutionalised throughout the innovation process rather than treated as a temporary feature of externally funded projects. Farmers should contribute to priority setting, technology design, experimentation, field validation, and evaluation because locally grounded knowledge improves the relevance and feasibility of innovations. Participatory trials, farmer research groups, innovation platforms, and continuous feedback mechanisms can embed knowledge co-production within research and extension institutions (Chambers, 1994; Pretty, 1995; Leeuwis, 2004; Norström et al., 2020).

Third, advisory systems should recognise agricultural innovation as a dynamic and iterative process rather than a one-time adoption decision. Farmers often move through stages of awareness, experimentation, adaptation, continued use, or rejection depending on perceived benefits, risks, resource constraints, and changing circumstances. Therefore, non-adoption and dis-adoption should be analysed as evidence of technology–context mismatch or institutional limitations rather than interpreted as farmer resistance. Understanding adoption as a learning process allows extension systems to improve innovation design and support adaptive management (Rogers, 2003; Douthwaite et al., 2009; Klerkx et al., 2012).

Fourth, digital agricultural services should follow a blended and rights-based approach that combines technological opportunities with human-centred advisory relationships. Public investment in connectivity, digital literacy, and locally appropriate content is essential, but digital platforms must also address concerns related to data ownership, privacy, transparency, and unequal access. Digital tools should complement rather than replace trusted extension relationships, particularly for marginalised farmers and decisions involving substantial economic or environmental risks (Trendov et al., 2019; Klerkx et al., 2019; Carolan, 2018).

Fifth, evaluation frameworks should be redesigned to reflect sustainability objectives rather than focusing primarily on numerical outputs such as farmers trained or technologies distributed. More meaningful indicators include farmer learning, confidence, inclusion, sustained practice change, reduced vulnerability, improved resource stewardship, collaboration, and institutional capacity for adaptation. Such indicators better capture the long-term outcomes expected from sustainable extension systems (Faure et al., 2012; Birner et al., 2009; Christoplos et al., 2012).

Finally, knowledge ecosystems require sustained institutional and financial support. Co-production depends on trust building, experimentation, relationship development, and organisational learning, processes that cannot be achieved through short-term project cycles alone. Development interventions frequently prioritise measurable outputs within limited timeframes, yet sustainable innovation requires investment in relationships, institutional capabilities, and long-term learning processes (Klerkx and Begemann, 2020; Lang et al., 2012). Public investment should therefore support not only technologies and infrastructure but also the human and institutional capacities required to maintain collaborative knowledge systems.

CONCLUSION

The persistent gap between agricultural knowledge and sustainable practice cannot be resolved by increasing information delivery alone. Conventional extension remains useful for clear and standardised messages, but it is inadequate for problems that require local adaptation, collective action and negotiation among competing objectives. Sustainable agriculture needs extension systems that combine scientific evidence with farmer experience and that create continuous feedback among research, practice and policy. Knowledge co-production offers a useful organising principle because it shifts attention from whether farmers received a message to whether institutions jointly produced a workable response. Its value lies not in participation as an end in itself, but in improving relevance, legitimacy, learning and accountability. Participatory field learning, farmer networks and digital services can all contribute, provided they are inclusive, transparent and connected to long-term institutional support. Agricultural extension should therefore be evaluated less by the number of technologies disseminated and more by its capacity to facilitate adaptive learning, sustained practice and equitable agricultural transformation. The most effective extension system is not the one that speaks most often to farmers, but the one that enables farmers and institutions to learn with one another and act on that learning.

Table 1. Practical design principles for knowledge co-production in extension.

Design principle	Operational implication	Evidence of progress
Start with farmer-defined problems	Use joint diagnosis before selecting technologies or messages.	Research and extension priorities reflect locally documented constraints.
Enable local experimentation	Support low-risk trials, comparison and adaptation.	Farmers can explain why practices were retained, modified or rejected.
Blend human and digital advice	Use digital tools for reach and data; use people for interpretation and trust.	Digital recommendations are verified, accessible and linked to follow-up.
Protect inclusion and rights	Address gender, tenancy, literacy, data ownership and representation.	Marginalised groups participate substantively and control use of their data.
Evaluate sustained outcomes	Track learning, continued use, resilience and resource stewardship.	Monitoring extends beyond training counts and initial adoption.

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