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Hybrid Agricultural Extension as an Inclusive Communication Strategy for Supporting Smart Agriculture: Evidence from Rural Indonesia

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ABSTRACT

Agricultural extension is undergoing significant transformation as digital technologies become increasingly integrated into agricultural innovation systems. However, empirical comparisons of conventional, digital, and hybrid extension approaches within the same rural context remain limited, particularly in developing countries. This study compared the effectiveness of these three extension models, identified barriers to digital technology adoption, and examined socio-demographic factors influencing farmers' adoption of digital agricultural technologies in Pasuruan Regency, Indonesia. An explanatory sequential mixed-methods design was employed, involving 100 farmers and 10 extension workers; quantitative data were analysed using descriptive statistics, one-way ANOVA, paired-sample t-tests, Pearson correlation, and multiple linear regression, while qualitative data were examined through thematic analysis. The hybrid model achieved the highest effectiveness score (4.67 ± 0.32), significantly outperforming conventional and digital approaches ($F(2,97) = 28.46$, $p < 0.001$), with participating farmers showing greater improvements in knowledge, productivity, and work efficiency. Education, digital literacy, and trust in extension workers were positively associated with technology adoption, whereas age showed a negative association. The findings indicate that hybrid agricultural extension is a more inclusive communication strategy that integrates interpersonal interaction with digital learning, strengthening agricultural innovation systems and supporting smart agriculture. These findings provide empirical evidence supporting hybrid extension as a sustainable communication model for accelerating smart agriculture adoption in developing countries.

Keywords: *agricultural extension, digital technology adoption, hybrid extension, rural communication, smart agriculture*

INTRODUCTION

Agriculture is undergoing a profound transformation driven by rapid advances in information and communication technologies, artificial intelligence, the Internet of Things, big data analytics, remote sensing, and precision agriculture. These innovations enable data-driven decision-making, improve resource-use efficiency, and strengthen resilience to climate change, making digitalization a key pathway toward sustainable and smart agriculture (FAO, 2023; OECD, 2023)

In this context, the role of agricultural extension has also been reshaped. Rather than a linear channel for transferring technology from researchers to farmers, extension increasingly functions as a platform for knowledge exchange, innovation facilitation, and collaborative learning among multiple stakeholders. From the Agricultural Innovation System (AIS) perspective, agricultural innovation is generated through interactions among researchers, extension workers, policymakers, agribusiness actors, and farmers rather than a linear process of technology transfer (Enciso et al., 2022; Gutiérrez Cano et al., 2023).

Consequently, smart agriculture reinforces this evolving role by requiring extension workers to facilitate farmers' access to digital knowledge, improve digital literacy, and encourage technology adoption through participatory learning (FAO, 2023).

Despite these developments, such demands are especially pressing in developing countries such as Indonesia, where digitalization proceeds alongside persistent disparities in education, digital literacy, and communication infrastructure. Although the Indonesian government has promoted smart farming and cyber extension, many farmers still rely on conventional extension because of limited digital competencies and unequal access to ICT-based advisory services. Older farmers typically possess extensive farming experience but lower digital readiness, whereas younger farmers are more familiar with technology, yet require practical guidance to apply it effectively (Sugihono et al., 2024).

Hybrid agricultural extension, which integrates face-to-face extension with digital learning technologies, has emerged as a promising response to these challenges. By combining interpersonal interaction, field demonstrations, and online communication, it enables continuous knowledge exchange while preserving the trust and collaborative relationships essential for innovation adoption. However, empirical evidence comparing the effectiveness of conventional, digital, and hybrid extension within the same institutional context remains limited, particularly in Indonesia. This study, therefore, investigates hybrid agricultural extension as an inclusive communication strategy for improving extension effectiveness, farmers' knowledge, technology adoption, and agricultural productivity (Sen et al., 2025).

Current Challenges and Recent Advances in Agricultural Extension

Building on this broader digitalization trend, several specific technologies have reshaped how agricultural information reaches farmers on the ground, including mobile applications, cloud-based advisory services, artificial intelligence, remote sensing, and geographic information systems (GIS) (FAO, 2023)

Digital communication has substantially improved the dissemination of weather information, market intelligence, crop management practices, and pest surveillance through online platforms and cyber extension services. However, its effectiveness depends not only on technological availability but also on farmers' digital literacy, educational background, and access to communication infrastructure, indicating that agricultural digitalization is a socio-technical transformation requiring investment in human resources and institutional capacity rather than infrastructure alone (Sen et al., 2025).

Digital literacy is a key determinant of farmers' ability to access, evaluate, and apply digital agricultural information (Johan et al., 2022), comparring competencies among extension workers, supported by reliable internet access, and improve their overall performance (Arfi et al., 2023). Nevertheless, interpersonal communication remains essential, since trust, direct interaction, and practical demonstration reduce uncertainty and encourage farmers to adopt innovations. Digital communication should, therefore, complement rather than replace conventional extension, particularly for smallholder farmers who rely on experiential learning and continuous mentoring (Sugihono et al., 2024).

These challenges reinforce the rationale for the hybrid extension approach introduced above, yet empirical evidence directly comparing conventional, digital, and hybrid extension within diverse rural contexts remains limited, particularly in Indonesia (FAO, 2023)

Research Gap and Theoretical Contribution

Recent studies have consistently demonstrated that digital technologies improve agricultural extension by expanding farmers' access to information, strengthening communication efficiency, and supporting technology dissemination through mobile applications, cyber extension, and online advisory services. These developments have accelerated agricultural digitalization and encouraged the adoption of smart agriculture in many countries. Nevertheless, existing studies have largely examined digital and conventional agricultural extension as separate communication approaches, providing limited evidence regarding the comparative effectiveness of hybrid agricultural extension within the same institutional and socio-economic context (FAO, 2023; OECD, 2023)

Another important limitation concerns the analytical focus of previous studies. Most research has investigated individual aspects of agricultural extension, such as digital literacy, technology adoption, communication effectiveness, and extension performance, without examining their combined influence on farmers' knowledge, participation, and agricultural productivity. Moreover, empirical evidence from Indonesia remains relatively limited, particularly regarding how farmers' socio-demographic characteristics influence the implementation and effectiveness of hybrid agricultural extension. These limitations indicate the need for a more comprehensive evaluation integrating technological, behavioural, and institutional dimensions of agricultural innovation (Sugihono et al., 2024).

A further gap exists at the theoretical level. Previous agricultural extension research has predominantly relied on a single theoretical perspective. Common examples include Diffusion of Innovation Theory, which explains technology adoption, and Andragogy, which explains adult learning processes. Although these theories provide valuable insights, they do not fully explain how communication channels, interpersonal trust, digital competencies, and institutional collaboration interact to influence agricultural innovation. Therefore, a more integrated conceptual perspective is required to explain the multidimensional nature of agricultural extension under conditions of rapid digital transformation (Knowles et al., 2015; Rogers, 2003).

To address these limitations, the present study proposes hybrid agricultural extension as an integrated communication strategy combining face-to-face extension with digital advisory services. Unlike previous studies that primarily compared conventional and digital extension separately, this study simultaneously evaluates conventional, digital, and hybrid extension using an explanatory sequential mixed-methods approach while integrating communication, innovation, and adult-learning perspectives. Consequently, the study contributes to both agricultural extension theory and practice by providing empirical evidence to support more inclusive and sustainable smart agriculture policies (Creswell & Creswell, 2023; FAO, 2023).

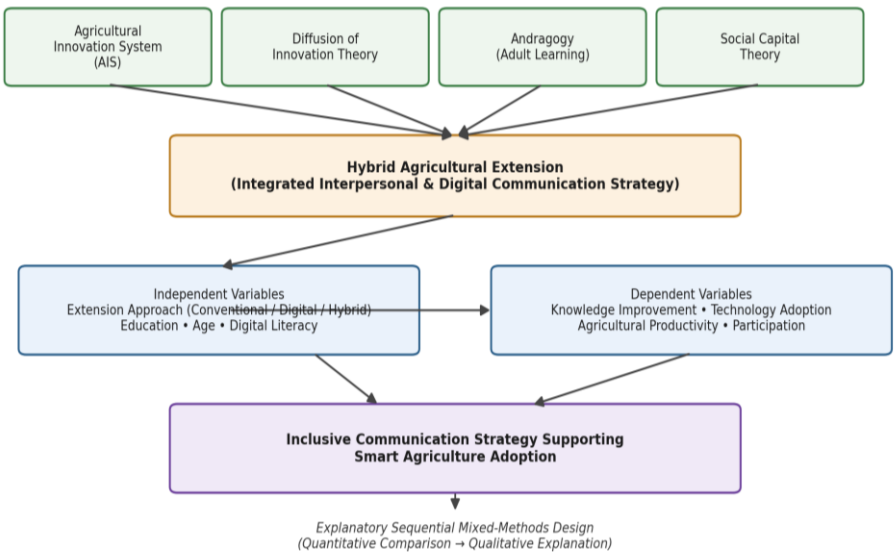

Figure 1. Conceptual framework linking the Agricultural Innovation System, Diffusion of Innovation Theory, Andragogy, and Social Capital Theory to hybrid agricultural extension, the study variables, and smart agriculture outcomes.

The novelty of this study is threefold. First, unlike previous research that has evaluated conventional and digital agricultural extension as separate, parallel communication approaches, this study simultaneously compares conventional, digital, and hybrid extension within a single institutional and socio-demographic context, thereby providing direct, within-context evidence of the comparative advantage of hybrid extension rather than inference across separate studies. Second, whereas prior studies have typically relied on a single theoretical lens or examined isolated determinants such as digital literacy or technology adoption alone, this study integrates the Agricultural Innovation System perspective, Diffusion of Innovation Theory, Andragogy, and Social Capital Theory into one coherent conceptual framework that jointly explains extension effectiveness, farmers' behavioural change, and technology adoption. Third, this integrated theoretical framework is empirically tested through an explanatory sequential mixed-methods design that combines quantitative comparison with qualitative explanation, offering a more comprehensive account of hybrid agricultural extension than studies relying on a single methodological approach. Taken together, these elements distinguish the present study from prior agricultural extension research and constitute its principal contribution to the field.

Research Objectives, Research Questions, and Study Contribution

Based on the identified research gaps, this study seeks to examine whether hybrid agricultural extension provides greater benefits than conventional and fully digital extension in improving farmers' knowledge, participation, agricultural productivity, and digital technology adoption. Specifically, the study addresses three major issues: (1) the comparative effectiveness of conventional, digital, and hybrid extension models; (2) the socio-demographic and technological factors influencing farmers' adoption of digital agricultural technologies; and (3) the contribution of hybrid agricultural extension to developing a more inclusive and sustainable smart agriculture system in Indonesia. Accordingly, the study hypothesizes that hybrid agricultural extension provides significantly better outcomes than conventional or fully digital approaches, while digital literacy and education positively influence technology adoption and age exerts a negative effect (Sugihono et al., 2024)

The study makes three important contributions to agricultural extension research. Theoretically, it integrates Diffusion of Innovation Theory, Andragogy, and the Agricultural Innovation System (AIS) perspective into a unified framework to explain how communication channels, experiential learning, and institutional collaboration jointly influence agricultural innovation and farmers' behavioural change. Methodologically, the use of an explanatory sequential mixed-methods design combines quantitative evaluation with qualitative inquiry, providing a more comprehensive understanding of agricultural extension effectiveness than studies relying on a single methodological approach. Practically, the findings are expected to support evidence-based policies by demonstrating that hybrid agricultural extension can integrate interpersonal communication with digital advisory services to strengthen farmers' digital readiness, improve agricultural productivity, and accelerate the implementation of smart agriculture in rural Indonesia. Consequently, this study contributes not only to the advancement of agricultural extension theory but also to the development of more adaptive, inclusive, and sustainable extension systems capable of responding to the challenges of agricultural digital transformation (Creswell & Creswell, 2023; OECD, 2023).

METHODS

This study employed an explanatory sequential mixed-methods design to comprehensively evaluate the effectiveness of hybrid agricultural extension as an inclusive communication strategy supporting smart agriculture in rural Indonesia. This design was selected because agricultural extension is not solely a technological intervention but also a multidimensional communication process involving behavioural change, institutional interaction, social learning, and technology adoption. Mixed-methods research enables the integration of quantitative findings with qualitative evidence, thereby providing a more comprehensive understanding of complex agricultural extension processes than the use of a single methodological approach (Creswell & Creswell, 2023; Tashakkori et al., 2021).

The quantitative phase was conducted first to compare the effectiveness of conventional, digital, and hybrid agricultural extension models and to identify socio-demographic determinants of digital technology adoption among farmers. Subsequently, qualitative data were collected through semi-structured interviews to explain and enrich the statistical findings by exploring farmers' communication experiences, learning preferences, and perceived barriers to adopting digital agricultural technologies. This sequential integration allows qualitative evidence to clarify the mechanisms underlying observed

quantitative relationships and enhances the interpretability of the overall findings (Creswell & Creswell, 2023; Tashakkori et al., 2021)..

The integration of quantitative and qualitative evidence was performed during the interpretation stage to strengthen the validity of the conclusions through methodological triangulation. Such integration is particularly appropriate for agricultural extension research because extension effectiveness cannot be adequately explained using quantitative indicators alone but also requires an understanding of farmers' perceptions, communication behaviour, and institutional contexts. Accordingly, the explanatory sequential mixed-methods design provides a rigorous framework for evaluating hybrid agricultural extension as a communication strategy supporting sustainable smart agriculture (Braun & Clarke, 2021; Creswell & Creswell, 2023)

Study Area

The research was conducted in Pasuruan Regency, East Java Province, Indonesia, one of the country's major agricultural production regions characterized by diverse farming systems, active farmer organizations, and well-established agricultural extension services. The regency has progressively implemented both conventional extension activities and ICT-based communication through WhatsApp discussion groups, cyber extension platforms, online advisory services, and digital learning materials. These characteristics provide an appropriate environment for examining the implementation of hybrid agricultural extension within a real-world agricultural setting (FAO, 2023)

Pasuruan Regency was selected purposively because it represents an area where conventional and digital extension systems coexist, enabling direct comparison among extension approaches within the same institutional context. Farmers in the regency also exhibited considerable variation in age, educational attainment, farming experience, commodity specialization, and digital literacy. Such diversity provides an appropriate empirical context for analysing socio-demographic factors influencing technology adoption and agricultural extension effectiveness while enhancing the relevance of the findings for other rural regions undergoing agricultural digital transformation (OECD, 2023; Sen et al., 2025).

Population and Sampling

The target population comprised farmers participating in agricultural extension programmes during the 2025 extension cycle in Pasuruan Regency, East Java, Indonesia. Agricultural extension workers were also included as key informants in the qualitative phase because of their direct involvement in planning and implementing extension activities. This combination of farmer and extension worker perspectives enabled a more comprehensive evaluation of hybrid agricultural extension from both participant and practitioner viewpoints, which is consistent with the explanatory sequential mixed-methods approach (Creswell & Creswell, 2023; FAO, 2023).

Purposive sampling was employed to select respondents who had direct experience with agricultural extension programmes and were able to provide relevant information regarding communication practices and technology adoption. A total of 100 farmers participated in the quantitative survey, while 10 agricultural extension workers were purposively selected for semi-structured interviews based on their professional experience with hybrid extension implementation. Purposive sampling is widely applied in agricultural and social research when respondents are selected according to predefined criteria relevant to the research objectives rather than through random selection (Creswell & Creswell, 2023; Etikan & Bala, 2017)

To facilitate comparative analysis, respondents were classified into three groups according to the dominant extension approach they experienced: conventional extension (n = 33), digital extension (n = 33), and hybrid extension (n = 34). The hybrid extension programme was implemented and observed over a five-month period (April–August 2025), allowing the study to assess changes in farmers' knowledge and agricultural productivity following participation in extension activities while ensuring comparable observations across extension models.

Operationally, the hybrid extension treatment combined scheduled face-to-face sessions with continuous digital communication. Face-to-face activities consisted of 10 group meetings and field demonstrations conducted biweekly throughout the five-month period, facilitated directly by agricultural extension workers. These sessions were complemented by digital communication delivered through a WhatsApp discussion group used for weekly scheduled information sharing and daily consultation whenever farmers had questions, short instructional videos distributed through the group, and access to a cyber

extension platform providing reference materials on recommended practices. Farmers in the hybrid group received the same technical content as those in the conventional and digital groups; the distinguishing feature of the hybrid treatment was the deliberate integration of interpersonal facilitation with these digital channels, rather than differences in subject matter. This protocol enabled a controlled comparison of extension effectiveness while holding informational content constant across the three groups.

Research Variables

The study examined the relationships between agricultural extension approaches, farmers' socio-demographic characteristics, digital technology adoption, and agricultural outcomes. The independent variables consisted of agricultural extension approach, education level, age, and digital literacy, whereas the dependent variables included farmers' knowledge improvement, agricultural productivity, participation in extension activities, and digital technology adoption. These variables were selected based on previous studies indicating that communication strategies, educational background, and digital competencies are among the primary determinants of agricultural innovation and technology adoption (Rogers, 2003; Sugihono et al., 2024)

Operational definitions and measurement indicators were established before data collection to ensure consistency in measurement and statistical analysis. Agricultural extension approach was measured as a nominal variable, while knowledge improvement, digital literacy, participation, and technology adoption were measured using interval scales. Agricultural productivity was recorded as crop yield per hectare, whereas education level and age were treated as socio-demographic predictors in the regression model. The operationalisation of variables followed established principles of quantitative research to enhance construct validity, analytical consistency, and the comparability of findings with previous agricultural extension studies (Creswell & Creswell, 2023; Hair et al., 2022).

Data Collection

Quantitative data were collected using a structured questionnaire developed from the study's conceptual framework and previous research on agricultural extension, digital technology adoption, and smart agriculture. The questionnaire consisted of 32 items distributed across four sections covering respondents' socio-demographic characteristics, participation in agricultural extension programmes, digital technology adoption, and perceptions of extension effectiveness. The instrument was designed to ensure consistency in data collection while allowing statistical comparison among conventional, digital, and hybrid extension groups (Creswell & Creswell, 2023; FAO, 2023)

Farmers' knowledge improvement was assessed using pre-test and post-test evaluations administered before and after participation in extension activities. Agricultural productivity was measured using crop yield records collected from respondents for the production period before and after programme implementation. To complement the quantitative findings, qualitative data were obtained through semi-structured interviews with agricultural extension workers and selected farmers representing the three extension approaches. Interviews explored communication experiences, learning preferences, barriers to digital technology adoption, and perceptions of hybrid agricultural extension. Field observations and institutional documents were also used to strengthen data triangulation and improve the credibility of the findings (Braun & Clarke, 2021; Creswell & Creswell, 2023)

Instrument Validity and Reliability

Prior to the main survey, the questionnaire was reviewed by experts in agricultural extension, communication, and agricultural education to evaluate the relevance, clarity, and comprehensiveness of the measurement items. A pilot study involving 30 farmers with characteristics comparable to the target population was subsequently conducted to improve instrument readability and assess its measurement performance before full-scale data collection. The pilot respondents were excluded from the main survey to avoid contamination of the final dataset. Expert review and pilot testing are widely recommended to enhance content validity and minimise measurement error in social science research (DeVellis & Thorpe, 2021; Hair et al., 2022)

Construct validity was evaluated using corrected item–total correlation, whereas internal consistency reliability was assessed using Cronbach's Alpha. Questionnaire items with corrected item–total correlation coefficients greater than 0.30 were retained, while Cronbach's Alpha values of at least 0.70

were considered acceptable indicators of internal consistency. In this study, Cronbach's Alpha for the questionnaire sections ranged from 0.82 to 0.91, indicating strong internal consistency. To strengthen the credibility and trustworthiness of the qualitative findings, triangulation was conducted by comparing interview results, field observations, and institutional documents. Member checking was also undertaken by returning interview summaries to selected participants to verify the accuracy of the interpretations and reduce researcher bias during qualitative analysis (Braun & Clarke, 2021; Hair et al., 2022).

Data Analysis

Quantitative data were analysed using IBM SPSS Statistics. Descriptive statistics were first employed to summarize respondents' socio-demographic characteristics and describe farmers' perceptions of agricultural extension programmes. Differences in extension effectiveness among conventional, digital, and hybrid extension models were examined using one-way analysis of variance (ANOVA) followed by Tukey's Honestly Significant Difference (HSD) post-hoc test to identify significant pairwise differences. Changes in farmers' knowledge and agricultural productivity before and after participation in extension activities were evaluated using paired-sample t-tests, while effect sizes were calculated to assess the practical significance of the observed differences. These statistical procedures are widely recommended for comparing group means and evaluating intervention outcomes in behavioural and agricultural research (Field, 2024; Hair et al., 2022)

Relationships between socio-demographic characteristics and digital technology adoption were initially examined using Pearson correlation analysis, followed by multiple linear regression to estimate the simultaneous effects of education level, age, and digital literacy on farmers' adoption of digital agricultural technologies. Prior to model estimation, assumptions of normality, multicollinearity, homoscedasticity, and linearity were assessed to ensure model validity. Statistical significance was determined at $p < 0.05$. Qualitative interview data were analysed using thematic analysis following the procedures of familiarisation, coding, theme development, review, and interpretation. The qualitative findings were subsequently integrated with quantitative results during the interpretation stage to provide contextual explanations for the observed statistical relationships, thereby strengthening the overall validity of the mixed-methods design (Braun & Clarke, 2021; Creswell & Creswell, 2023)

Ethical Considerations

The study was conducted in accordance with the fundamental principles of research ethics, including voluntary participation, informed consent, confidentiality, and respect for participants' rights. Before data collection, all respondents received information regarding the research objectives, study procedures, and the intended use of the collected data. Participation was entirely voluntary, and respondents were informed that they could withdraw from the study at any stage without any consequences. Personal identities and individual responses were treated confidentially and reported only in aggregated form to protect participants' privacy (World Medical Association, 2024)

To enhance research integrity, qualitative findings were verified through member checking and data triangulation involving interview transcripts, field observations, and institutional documents. Data were stored securely and used exclusively for academic purposes. Throughout the research process, the study adhered to internationally recognised principles of transparency, confidentiality, and responsible research conduct, ensuring that the rights and welfare of participants were protected while maintaining the credibility and trustworthiness of the research findings (Braun & Clarke, 2021; Creswell & Creswell, 2023).

RESULTS AND DISCUSSION

A total of 100 farmers participated in the quantitative survey, comprising 33 respondents in the conventional extension group, 33 respondents in the digital extension group, and 34 respondents in the hybrid extension group. The relatively balanced distribution of respondents provided an appropriate basis for comparing the effectiveness of the three agricultural extension approaches while minimizing group-size bias during statistical analysis (Creswell & Creswell, 2023; Hair et al., 2022)

The socio-demographic characteristics indicate that the farming population was predominantly male (78%), while female farmers accounted for 22%. Most respondents (58%) were over 50 years old, suggesting that agricultural activities in the study area are still dominated by older farmers. Regarding

educational attainment, elementary school (34%) and junior high school (28%) were the most common levels of education, while only 8% of respondents had completed tertiary education. In addition, 43% of respondents had more than twenty years of farming experience.

Overall, the respondent profile reflects typical characteristics of smallholder farmers in rural Indonesia, where long farming experience coexists with limited formal education and varying levels of digital literacy. Such conditions are consistent with previous findings that digital readiness in rural farming communities is often shaped by disparities in education, experience, and access to information technologies (Johan et al., 2022; Sirajuddin & Kamba, 2021).

Comparative Effectiveness of Agricultural Extension Models

The comparative analysis demonstrated statistically significant differences in the effectiveness of the three agricultural extension approaches evaluated in this study. Among the extension models, the hybrid agricultural extension approach achieved the highest mean effectiveness score (4.67 ± 0.32), followed by the conventional extension model (4.21 ± 0.39) and the digital extension model (3.85 ± 0.46). These descriptive results indicate observable differences in extension performance across the three communication approaches.

The one-way analysis of variance (ANOVA) confirmed that the observed differences were statistically significant ($F(2,97) = 28.46$; $p < 0.001$). The calculated effect size ($\eta^2 = 0.37$) represents a large practical effect, indicating that approximately 37% of the variation in agricultural extension effectiveness was explained by differences in extension approaches. According to established statistical guidelines, this magnitude suggests substantial differences among the three extension models rather than random variation (Cohen, 1988; Hair et al., 2022)

Post-hoc comparisons using Tukey's HSD test confirmed the pairwise pattern summarized in Table 2: the hybrid model significantly outperformed both the conventional and digital models, and conventional extension significantly exceeded digital extension (all $p < 0.05$).

Overall, the statistical analyses demonstrate that the extension model adopted was associated with significant variation in measured extension effectiveness. The descriptive statistics, ANOVA results, effect size estimates, and post-hoc comparisons collectively provide quantitative evidence supporting differences in performance among conventional, digital, and hybrid agricultural extension approaches within the study population (Creswell & Creswell, 2023; Field, 2024)

The findings demonstrate that the hybrid agricultural extension model was more effective than both conventional and fully digital extension approaches in improving overall extension performance. This result indicates that combining face-to-face interaction with digital communication creates a more comprehensive learning environment for farmers than relying on a single communication channel. Rather than replacing conventional extension, digital technologies appear to complement interpersonal communication by providing continuous access to agricultural information while maintaining direct interaction between farmers and extension workers. Similar conclusions have been reported in recent studies, which emphasize that integrating digital technologies with conventional extension enhances communication effectiveness, knowledge exchange, and farmer participation in agricultural innovation (Purwatiningsih et al., 2018; Suratini et al., 2021)

The superior performance of hybrid extension is consistent with the growing body of literature on agricultural digitalization. Previous studies have shown that digital platforms, such as mobile applications, online advisory services, and social media, increase the accessibility and timeliness of agricultural information. However, these technologies are most effective when combined with field demonstrations, group discussions, and direct consultation, enabling farmers to verify information and adapt recommended practices to local conditions. Consequently, hybrid extension supports continuous learning while preserving the social interaction that remains essential for effective agricultural communication (OECD, 2023)

The findings can be explained through Diffusion of Innovation Theory, which argues that communication channels strongly influence the adoption of new technologies. Face-to-face communication reduces uncertainty by allowing farmers to observe innovations directly, discuss implementation challenges, and receive immediate feedback from extension workers. Digital communication complements this process by expanding access to information beyond scheduled extension activities, thereby reinforcing learning and supporting continuous innovation. The integration

of these complementary communication channels accelerates the diffusion of agricultural innovations while improving farmers' confidence in adopting new technologies (Rogers, 2003)

From a practical perspective, these findings suggest that future agricultural extension systems should prioritize hybrid communication strategies rather than replacing conventional extension with fully digital services. Investments in digital platforms should therefore be accompanied by strengthening extension workers' communication competencies, expanding digital infrastructure, and maintaining participatory learning approaches that foster trust and collaboration. Such an integrated strategy is expected to enhance the effectiveness, inclusiveness, and sustainability of agricultural extension programmes while supporting the implementation of smart agriculture in rural areas (Arangurí et al., 2025; OECD, 2023).

Knowledge and Productivity Improvement

Participation in agricultural extension programmes was associated with significant improvements in both farmers' technical knowledge and agricultural productivity. The descriptive analysis showed that the average knowledge score increased from 52.3 ± 8.21 before participation to 80.6 ± 7.12 after participation, representing an average gain of 28.3 points. Paired-sample t-test analysis confirmed that this increase was statistically significant ($t = 16.84$, $p < 0.001$). The corresponding effect size (Cohen's $d = 1.28$) indicates a very large practical effect, demonstrating a substantial improvement in farmers' knowledge following participation in agricultural extension activities (Cohen, 1988; Field, 2024)

A similar pattern was observed for agricultural productivity. Average crop yield increased from 47.6 ± 5.74 to 56.3 ± 5.18 quintals ha^{-1}, corresponding to an improvement of approximately 18.2% after participation in extension programmes. The paired-sample t-test showed that this difference was statistically significant ($t = 9.72$, $p < 0.001$), while the calculated effect size (Cohen's $d = 0.98$) also represented a large practical effect, indicating meaningful changes in production performance during the study period (Cohen, 1988; Hair et al., 2022)

Comparative results among extension approaches further indicated that farmers participating in the hybrid agricultural extension programme achieved the greatest improvements in production outcomes, based on interviews and programme records. Crop productivity increased by 24.0%, while work efficiency improved by 25.3%, with both indicators demonstrating statistically significant differences ($p < 0.001$). These findings consistently show that measurable improvements in knowledge acquisition and agricultural performance occurred following participation in agricultural extension programmes, particularly among respondents involved in the hybrid extension model.

Overall, the statistical evidence demonstrates that participation in agricultural extension was associated with significant improvements in both learning outcomes and agricultural productivity. The magnitude of the observed effect sizes indicates that the improvements were not only statistically significant but also practically meaningful within the study population (Field, 2024; Hair et al., 2022)

The present study demonstrates that participation in agricultural extension programmes substantially improved farmers' knowledge and agricultural productivity, with the most pronounced gains observed among participants in the hybrid extension model. These results suggest that effective agricultural extension contributes not only to the dissemination of technical information but also to strengthening farmers' capacity to apply new knowledge in farming practices. Previous studies similarly report that extension programmes integrating digital technologies with participatory learning approaches enhance farmers' technical competencies and facilitate more effective decision-making in crop management (Arangurí et al., 2025)

The observed improvement in agricultural productivity can be attributed to the complementary functions of face-to-face communication and digital learning. Conventional extension provides opportunities for field demonstrations, practical problem-solving, and direct interaction with extension workers, whereas digital platforms enable continuous access to technical information, weather forecasts, and market updates. Together, these communication channels reinforce learning through repeated exposure to information and timely technical support, thereby improving farmers' ability to implement recommended agricultural practices. Similar evidence has been reported in studies showing that blended extension approaches increase learning effectiveness and accelerate the adoption of improved farming technologies (OECD, 2023)

These findings are consistent with Andragogy, which emphasizes that adult learners acquire knowledge most effectively when learning is directly connected to their practical experiences and immediate needs.

Farmers generally learn through observation, experimentation, discussion, and reflection rather than through passive information transfer. The hybrid extension model supports these principles by combining experiential learning in the field with continuous digital access to agricultural knowledge, allowing farmers to reinforce new skills and adapt innovations to local production conditions. Consequently, hybrid extension provides a more flexible and learner-centred approach than either conventional or fully digital extension implemented independently (Knowles et al., 2020; Rogers, 2003)

From a practical perspective, these findings highlight the importance of designing agricultural extension programmes that integrate digital advisory services with participatory field-based learning. Policymakers should therefore prioritize investments not only in digital infrastructure but also in strengthening extension workers' facilitation skills, demonstration activities, and farmer learning networks. Such integrated strategies are expected to improve farmers' knowledge, enhance agricultural productivity, and strengthen the long-term sustainability of smart agriculture initiatives, particularly in rural areas where digital readiness remains uneven (FAO, 2023; OECD, 2023).

Determinants of Digital Technology Adoption

The analysis identified several barriers affecting farmers' adoption of digital agricultural technologies. The most frequently reported constraint was the high cost of internet access, experienced by 68% of respondents, followed by limited digital literacy (52%), resistance among older farmers (45%), and inadequate internet connectivity (17%). These results support the view that both technological and human-related factors were reported as constraints to the utilization of ICT-based agricultural extension services, consistent with prior evidence that farmers' perceptions of ICT implementation in extension are shaped by similar technological and human-related barriers (Sirajuddin & Liskawati Kamba, 2021). This pattern is also broadly consistent with barrier studies in other developing-country contexts, where cost, connectivity, and digital literacy gaps have similarly been identified as primary obstacles to ICT-based agricultural information access (Anteneh & Melak, 2024; Shemfe & Modirwa, 2026; Suardipa et al., 2025).

Pearson correlation analysis showed a strong positive relationship between farmers' trust in agricultural extension workers and digital technology adoption ($r = 0.724$, $p < 0.001$). The positive correlation suggests that respondents with higher levels of trust in extension workers also reported greater use of digital agricultural technologies. This relationship indicates a substantial association between interpersonal trust and farmers' participation in ICT-based agricultural advisory services.

Multiple linear regression analysis further demonstrated that the proposed regression model significantly explained variations in digital technology adoption, accounting for 54.1% of the observed variance ($F = 37.24$, $p < 0.001$, $R^2 = 0.541$). Among the explanatory variables, digital literacy exhibited the strongest positive effect on technology adoption ($\beta = 0.386$, $p < 0.001$), followed by education level ($\beta = 0.324$, $p = 0.001$). Conversely, age showed a significant negative relationship ($\beta = -0.452$, $p < 0.001$), indicating lower adoption levels among older respondents.

Diagnostic tests confirmed that the regression model satisfied the assumptions required for multiple linear regression analysis. Variance Inflation Factor (VIF) values ranged from 1.27 to 1.42, indicating the absence of multicollinearity among the predictor variables. In addition, the Durbin–Watson statistic of 1.97 suggested that residuals were independent. Collectively, this pattern confirms that the regression model was statistically appropriate for examining the influence of socio-demographic characteristics on farmers' adoption of digital agricultural technologies (Field, 2024; Hair et al., 2022).

The evidence suggests that farmers' adoption of digital agricultural technologies is influenced by both socio-demographic characteristics and communication-related factors. Digital literacy emerged as the strongest positive determinant of technology adoption, whereas age showed a significant negative relationship. In addition, farmers' trust in agricultural extension workers was positively associated with the utilization of ICT-based advisory services. These findings suggest that successful digital transformation in agriculture depends not only on the availability of digital technologies but also on farmers' capacity to access, understand, and confidently apply digital information in agricultural decision-making. Similar patterns have been reported in recent studies highlighting digital literacy and interpersonal trust as key drivers of technology adoption in rural agricultural communities (FAO, 2023; Sugihono et al., 2024).

The negative influence of age and the positive effects of education and digital literacy are consistent with previous studies demonstrating that younger and more educated farmers generally exhibit greater

readiness to adopt agricultural innovations. Farmers with stronger digital competencies are better able to evaluate online information, utilize mobile-based advisory services, and integrate digital recommendations into farming practices. However, these findings also suggest that technological readiness alone is insufficient without adequate institutional support and continuous extension services that help farmers translate digital information into practical agricultural actions. Similar conclusions have been reported in studies examining agricultural digitalization in developing countries, where disparities in education, infrastructure, and communication access continue to shape technology adoption outcomes (Sen et al., 2025). Comparable evidence from smallholder contexts likewise shows that farmers' willingness to adopt digital application tools and paid digital advisory services is closely tied to perceived usefulness, socio-demographic characteristics, and prior exposure to smart farming (Abioye et al., 2024; Amoussouhoui et al., 2024) while evidence from other developing regions likewise shows that hybrid models combining digital tools with continued human facilitation yield stronger and more sustained advisory outcomes than purely digital approaches (Wang & Zhang, 2021)

From a theoretical perspective, these findings can be explained through Diffusion of Innovation Theory, which proposes that innovation adoption is strongly influenced by communication channels, perceived innovation characteristics, and social interaction among potential adopters (Rogers, 2003). Furthermore, the findings support the perspective of Social Capital Theory, which emphasizes that trust, social networks, and collaborative relationships reduce uncertainty and facilitate collective learning. In the context of agricultural extension, extension workers function not only as information providers but also as trusted intermediaries who strengthen farmers' confidence in adopting digital technologies and adapting innovations to local farming conditions (Putnam, 2009; Rogers, 2003). This intermediary role has similarly been documented among extension workers elsewhere in East Java during the ongoing digital transformation of extension services (Salsabella et al., 2024).

These findings have important implications for agricultural development policies. Expanding internet infrastructure alone is unlikely to accelerate digital transformation unless accompanied by programmes that improve farmers' digital literacy, strengthen extension workers' digital competencies, and encourage participatory communication between farmers and extension institutions. Accordingly, hybrid agricultural extension offers a strategic pathway for reducing the rural digital divide by integrating interpersonal communication with digital advisory services. Such an approach is expected to promote more inclusive technology adoption, strengthen farmers' adaptive capacity, and support the long-term implementation of smart agriculture in Indonesia and other developing countries (FAO, 2023; OECD, 2023).

Theoretical and Practical Implications of Hybrid Agricultural Extension

The present study contributes to the growing body of agricultural extension literature by demonstrating that the effectiveness of hybrid agricultural extension cannot be explained solely through technological advancement. Instead, the observed relationship implies that successful agricultural innovation results from the interaction between digital communication, interpersonal relationships, and farmers' learning processes. This evidence extends previous agricultural extension research, which has frequently examined digital technologies, communication effectiveness, or technology adoption independently. By integrating these dimensions within a single analytical framework, the study provides a more comprehensive understanding of how hybrid agricultural extension supports knowledge exchange, innovation diffusion, and sustainable agricultural development (FAO, 2023; OECD, 2023). This is in line with the agricultural innovation system perspective, which conceptualizes extension, research and development, training, and sustainability as interdependent subsystems whose coordination determines the effectiveness of innovation diffusion among farmers (Enciso et al., 2022; Gutiérrez Cano et al., 2023)

From a theoretical perspective, the study reinforces the complementary roles of Diffusion of Innovation Theory, Social Capital Theory, and Andragogy in explaining farmers' adoption of agricultural innovations. Diffusion of Innovation Theory emphasizes the importance of communication channels in accelerating technology adoption, while Social Capital Theory highlights the contribution of trust, social networks, and collaborative relationships in reducing uncertainty during technological change. Meanwhile, Andragogy explains that adult farmers learn most effectively through practical experience, active participation, and problem-oriented learning. The integration of these theoretical perspectives suggests that hybrid agricultural extension provides a more comprehensive explanation of farmers' behavioural change than reliance on a single theoretical framework (Knowles et al., 2020; Rogers, 2003).

The findings also have important practical implications for strengthening agricultural The findings also have important practical implications for strengthening agricultural extension systems in Indonesia and other developing countries. Investments in digital agriculture should be accompanied by continuous capacity-building programmes that improve farmers' digital literacy and strengthen extension workers' competencies in digital communication and facilitation. Furthermore, agricultural extension institutions should promote hybrid learning environments by integrating field demonstrations, farmer group discussions, digital advisory platforms, and online knowledge-sharing mechanisms. Such integrated strategies are expected to improve extension effectiveness while reducing disparities in farmers' access to agricultural information and innovation (FAO, 2023; Sugihono et al., 2024)

From a policy perspective, the study supports the development of more inclusive agricultural extension systems capable of responding to the challenges of digital transformation and sustainable agriculture. Rather than replacing conventional extension services, policymakers should encourage the integration of interpersonal communication with ICT-based advisory services through coordinated institutional support, improved digital infrastructure, and continuous professional development for extension personnel. Strengthening these complementary components will contribute to more resilient agricultural innovation systems, accelerate the implementation of smart agriculture, and enhance the long-term sustainability of rural development programmes (Sen et al., 2025).

Study Limitations and Future Research Directions

Despite providing important contributions to the literature on agricultural extension and smart agriculture, this study has several limitations that should be acknowledged. First, the research was conducted in a single regency in East Java, Indonesia, which may limit the generalisability of the findings to other agricultural regions with different socio-economic, institutional, and agroecological characteristics. Agricultural extension systems vary considerably across regions in terms of infrastructure, farmer organizations, institutional capacity, and access to digital technologies. Therefore, caution should be exercised when applying these findings to broader national or international contexts (Creswell & Creswell, 2023).

Second, the study employed a five-month observation period, which was sufficient to evaluate short-term changes in farmers' knowledge, participation, and agricultural productivity but may not fully capture the long-term sustainability of hybrid agricultural extension. Technology adoption and behavioural change are dynamic processes that often require continuous interaction, repeated learning, and institutional support over extended periods. Consequently, longitudinal studies are needed to investigate whether the observed improvements can be sustained over time and how hybrid agricultural extension influences long-term agricultural resilience and innovation capacity (Rogers, 2003)

Another limitation relates to the explanatory variables included in the regression model. Although education level, age, and digital literacy explained a substantial proportion of the variation in digital technology adoption, other potentially influential factors such as farm size, household income, institutional support, market accessibility, social networks, farmers' risk perception, and access to agricultural finance were not incorporated into the present analysis. Including these variables in future studies would provide a more comprehensive understanding of farmers' technology adoption behaviour and strengthen the explanatory power of agricultural extension research (Hair et al., 2022; Sen et al., 2025).

Future research should therefore extend this work by conducting comparative studies across multiple provinces or countries, employing longitudinal research designs, and integrating emerging digital technologies such as artificial intelligence, Internet of Things (IoT), remote sensing, and big data analytics into hybrid agricultural extension systems. Recent evidence suggests that such technologies accelerate the adoption of climate-smart and precision agricultural practices most effectively when they remain embedded within continued extension facilitation rather than deployed as stand-alone digital tools. Further investigation should also explore the role of institutional collaboration, public–private partnerships, and agricultural innovation ecosystems in supporting inclusive digital transformation. Such studies are expected to generate stronger empirical evidence for designing adaptive, resilient, and sustainable agricultural extension systems capable of accelerating smart agriculture in developing countries (FAO, 2023; OECD, 2023)

CONCLUSION

This study demonstrates that hybrid agricultural extension represents a more effective and inclusive communication strategy than either conventional or fully digital extension in supporting smart agriculture in rural Indonesia. By integrating face-to-face communication with digital advisory services, the hybrid extension model significantly improved extension effectiveness, farmers' knowledge, agricultural productivity, participation in extension activities, and digital technology adoption. These findings confirm that digital technologies generate greater benefits when they complement interpersonal communication rather than replace it, thereby creating a continuous learning environment while maintaining the trust, interaction, and collaboration that are fundamental to agricultural innovation.

The study also confirms that farmers' socio-demographic characteristics play an important role in determining the adoption of digital agricultural technologies. Digital literacy emerged as the strongest determinant of technology adoption, followed by educational attainment, whereas age was negatively associated with farmers' willingness to utilize ICT-based agricultural services. These findings suggest that successful agricultural digital transformation depends not only on technological infrastructure but also on strengthening farmers' digital competencies, improving extension workers' facilitation skills, and promoting inclusive learning environments that accommodate diverse farmer characteristics.

This research contributes to agricultural extension theory and practice by proposing hybrid extension as an integrated communication model combining interpersonal interaction with digital learning technologies. Integrating Diffusion of Innovation Theory, Andragogy, and the Agricultural Innovation System perspective, together with an explanatory sequential mixed-methods design, provides a more comprehensive understanding of how communication, adult learning, and institutional collaboration jointly support agricultural innovation and technology adoption. Practically, the findings support agricultural extension policies that integrate field demonstrations, farmer field schools, digital advisory platforms, and continuous capacity-building programmes, accompanied by initiatives that enhance digital literacy and strengthen extension workers' digital competencies. Such integrated strategies are expected to accelerate agricultural modernization while reducing the digital divide among rural farming communities.

Although the study provides valuable empirical evidence, its findings are limited to one regency and a single extension cycle. Future research should employ longitudinal and multi-regional designs involving more diverse farming communities and incorporate additional variables, such as institutional support, farm economic capacity, market access, social networks, and emerging digital technologies. Such efforts will provide a more comprehensive understanding of the long-term contribution of hybrid agricultural extension to sustainable and inclusive smart agriculture.

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