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AgriTech Innovation and Food Security: Balancing Technological Disruption and Smallholder Inclusion

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ABSTRACT

Global food security faces mounting challenges from climate change, market volatility, and limited access to nutritious food. Agricultural technology innovation (AgriTech) offers solutions to enhance productivity, yet smallholder adoption remains hindered by costs, digital literacy gaps, and infrastructure limitations. This research evaluates the balance between agronomic efficiency and social inclusion in AgriTech implementation, identifies effective extension models, and formulates equity-oriented policy recommendations. Using a qualitative case study approach, data were collected from 25 smallholder farmers in rural Indonesia through in-depth interviews, field observations, and questionnaires (50 respondents), then analyzed using Miles and Huberman's interactive model combined with descriptive statistics. Results demonstrate that AgriTech increases productivity by an average of 12% per planting season and reduces input costs, yet significant barriers persist including application fees, limited internet access, and low digital literacy. Blended extension approaches (combining face-to-face and digital counseling) and collective institutional strengthening prove effective in expanding adoption. Findings indicate that 46% of farmers consider subscription costs prohibitive, 38% face network limitations, and 33% lack digital skills. This research confirms that sustainable food security requires balancing technological disruption with smallholder inclusion. Policy implications include subsidizing application access, integrating fintech with digital advisory services, and implementing digital literacy programs to strengthen farmers' capacity for technological innovation utilization.

INTRODUCTION

Global food security faces increasingly complex multidimensional challenges driven by climate change, population growth, rapid urbanization, and economic volatility. Climate impacts on agriculture are severe: an average temperature increase of +1°C can reduce corn yields by 7.5%, wheat by 6.0%, soybeans by 6.8%, and rice by 1.2%, even with adaptation measures (Hu et al., 2024; Hultgren et al., 2025; Lobell et al., 2025). This confirms technological innovation is urgently needed to maintain global food production capacity amid escalating climate shocks.

Economic access to nutritious food remains critically limited. The State of Food Security and Nutrition in the World (SOFI) 2024 report indicates that 2.6 billion people cannot afford a healthy diet in 2024, despite a slight decrease from 2.826 billion in 2022 (Headey et al., 2024; Herforth et al., 2025). The average global cost of a healthy diet reached US$4.46 PPP per day in 2024, unaffordable for most poor households in developing countries (World Bank, 2025). Food security thus encompasses not only availability but also affordability of nutritious food across all societal levels.

Agricultural technology innovation (AgriTech)—including sensors, automation, drones, artificial intelligence, and machine learning—has emerged as a promising solution, enabling more efficient and sustainable precision agriculture (Anastasiou et al., 2023; Getahun et al., 2024). AgriTech improves water and nutrient use efficiency, reduces fertilizer waste, and enhances crop quality (Padhiary et al., 2024; Saha et al., 2025). However, adoption remains unevenly distributed. Smallholders managing less than 2 hectares of land contribute approximately 35% of global food production yet face capital barriers, digital literacy gaps, and limited infrastructure access (Lowder et al., 2021; Ricciardi et al., 2021).

This access gap risks social and economic exclusion. Agricultural platformization may centralize value to digital infrastructure owners, create information asymmetry, and weaken smallholder bargaining positions (Rotz et al., 2019; Van der Burg et al., 2019; Sarku et al., 2025). Without inclusive regulations and data governance, technological disruption could exacerbate food system inequality (Canfield, 2024). Empirical evidence on AgriTech's impact on smallholders remains mixed. Meta-analyses show digital interventions can improve outcomes and income, but field results are often inconsistent, contingent on extension support and socio-economic contexts (Beach et al., 2025; Ding et al., 2022; Schulz et al., 2023).

Digital financial integration offers new opportunities. Mobile money and fintech services strengthen household food security by facilitating input transactions, savings, remittances, and faster capital access for smallholders (Yao & Hernandez, 2023; Atta-Aidoo et al., 2024; Ky et al., 2025). Effectiveness, however, depends on digital literacy and local supporting ecosystems. Thus, this research urgency lies in balancing technological disruption potential with smallholder inclusion needs as primary actors in the global food chain.

Success in food sector technological innovation is measured not only by agronomic efficiency but also by equitable benefit distribution. Previous research focused heavily on technology adoption or technical performance without systematically linking to inclusion indicators such as healthy diet affordability, digital finance access, and smallholder data rights (Klerkx & Rose, 2019; Ingram et al., 2022). A research gap exists on how AgriTech can deliver dual benefits: increasing productivity while ensuring access and fairness for smallholders.

This research offers analytical novelty by providing a framework balancing disruption and inclusion. First, it integrates agronomic efficiency indicators (crop yields, input intensity) with inclusion indicators (nutrition access, digital financing access, data governance). Second, it identifies design principles for blended advisory models and transparent agricultural data governance. Third, it proposes an AgriTech portfolio prioritization matrix for smallholders tailored to local climate risks.

Therefore, this study aims to: evaluate trade-offs between efficiency and inclusion in AgriTech use, identify institutional mechanisms reducing exclusion risk, and provide evidence-based policy recommendations supporting global food system sustainability. This research contributes theoretically to agricultural innovation literature and practically to policymakers, investors, and smallholder communities at the forefront of global food security.

RESEARCH METHODS

Types of Research

This research uses a qualitative approach with a comparative case study design, chosen to understand in depth how AgriTech innovations affect food security, particularly smallholder inclusion. The case study enables contextual analysis of AgriTech implementation practices in Indonesian smallholder communities.

Population and Sample

The research population includes all smallholders in the region who have adopted digital agricultural technology (precision farming tools, application-based extension services, agricultural fintech services). Purposive sampling applies the following criteria: (1) farmers manage <2 hectares of land, (2) have used at least one AgriTech type for ≥1 year, and (3) willingly participate. Samples also include agricultural extension workers, app developers, and village government/agricultural agency representatives. Sample size of 20-30 participants for in-depth interviews ensures theoretical saturation in qualitative case studies, while 50-70 questionnaire respondents provide sufficient statistical variation for descriptive analysis (Creswell, 2020; Morse, 2022).

Research Instruments

The main instrument is a semi-structured interview guide that contains the theme of technology adoption, experience of use, barriers, benefits, and its impact on food access and income. In addition, the questionnaire instrument was used to obtain simple quantitative data related to farmer profiles, intensity of technology use, perception of benefits, and affordability of healthy food. Observation instruments are also used to record field practices, farmers' interactions with applications/tools, and the dynamics of input and yield distribution.

Data Collection Techniques

Data is collected through three main techniques:

1. In-depth interviews with smallholders, extension workers, and AgriTech service providers.
2. The survey questionnaire is simple to complement the interview data, especially regarding the intensity of technology use and access to food.
3. Participatory observation in agricultural land to see firsthand the application of AgriTech, interaction between farmers, and socio-economic context in the field.

Research Procedure

The research is carried out through five main stages:

1. Literature review to formulate AgriTech efficiency and inclusion indicators.
2. Field coordination with the village government/farmer groups to determine locations and participants.
3. Primary data collection through interviews, observations, and questionnaires.
4. Data validation through *source triangulation* (comparing the results of interviews, observations, and questionnaires).
5. Data analysis and interpretation of results adjusted to the disruption-inclusion balance theory framework.

Data Analysis Techniques

Qualitative data analysis is carried out with the Miles and Huberman interactive model which includes data reduction, data presentation, and conclusion drawn/verification. Data from the

interviews were thematically coded to find key patterns and categories such as "benefits of AgriTech", "barriers to adoption", and "impact on food access".

RESULTS AND DISCUSSION

Respondent Profile and Socio-Economic Context

The study respondents consisted of 25 smallholders with an average land area of 1.2 hectares, five field agricultural extension workers, two village government representatives, and three AgriTech application developers. The majority of farmers are 35-55 years old, with a formal level of junior and senior high school education. The results of the questionnaire showed that 68% of respondents were new to AgriTech applications in the last 2–3 years, while another 32% had more than 5 years of experience (Headey et al., 2024; Ricciardi et al., 2021; Ky et al., 2025). This confirms that the use of AgriTech among smallholder farmers is still relatively new and in the early adoption stage.

The socioeconomic background of the respondents showed a high dependence on major food commodities, such as rice and maize, as well as seasonal horticultural crops. Most household income comes from agricultural produce, with additional contributions from other informal jobs. An interview with one of the farmers stated that income increased by about 15% after using the fertilizer recommendation app, although market price fluctuations remained a challenge. Previous studies have emphasized that technology adoption does contribute to increased productivity, but income stability is strongly influenced by market prices (Saha et al., 2025; Lobell et al., 2025; Yao & Hernandez, 2023).

Demographic factors also affect the adoption rate. Younger farmers tend to master digital applications faster, while farmers over 55 are more reliant on extension workers for data interpretation. Field observations showed that farmer groups consisting of young members were more active in discussing application features, while senior farmer groups were more passive. This is in line with research findings that digital literacy and age are closely related to the ability to adopt agricultural technology (Coggins et al., 2022; Herforth et al., 2025; Atta-Aidoo et al., 2024).

The gender aspect plays an important role in the adoption of technology. About 40% of female respondents are more active in using applications to check market prices than men. In an interview, a female farmer stated: *"I use an app to know the price of chili peppers and tomatoes, so that I don't lose money when selling."* This phenomenon is consistent with the literature that emphasizes the role of women as decision-makers in households and as agents of digital innovation adoption (Lowder et al., 2021; Lee et al., 2025; Ky et al., 2025).

Education level is also a factor that affects respondents' understanding. Farmers with a high school background show better skills in accessing and understanding weather data and fertilization recommendations compared to those who only graduate from junior high school. Previous studies have found that education level is one of the significant variables that explain the variation in the success of AgriTech adoption (Hultgren et al., 2025; Rotz et al., 2019; Van der Burg et al., 2019). The results of the observation also show that there is an inequality of access between regions. Respondents in villages with stable internet networks were more able to make optimal use of application features, while respondents in villages with limited networks only took advantage of basic features. One of the extension workers stated: *"The signal in our village is often lost, farmers sometimes cannot access the application when they need it quickly."*

This condition confirms that digital infrastructure is a key factor in the distribution of technological benefits (Canfield, 2024; Sarku et al., 2025; Ingram et al., 2022). Thus, the respondents' profiles show diversity in age, gender, education, and access to digital infrastructure. This diversity has a direct impact on the adoption and utilization rate of AgriTech. These findings are consistent with the literature that asserts that the adoption of technology in the agricultural sector

cannot be separated from the social, economic, and cultural contexts of smallholder farmers (Beach et al., 2025; Ding et al., 2022; Schulz et al., 2023).

Table 1. Socio-Economic Profile of Research Respondents

Characteristic	Number of Respondents	Percentage (%)
Man	15	60
Woman	10	40
Age <35 years old	5	20
Age 35–55 years old	15	60
Age >55 years old	5	20
Junior High ≤ Education	14	56
High school education and above	11	44
New AgriTech Users	17	68
Existing users (>5 yrs)	8	32

This table shows that the majority of respondents are productive-age men with secondary education, and most of them have only used AgriTech in the last 2–3 years. This data shows that the research is in the context of smallholders who are still in the early stages of technology adoption.

The Impact of AgriTech on Productivity and Efficiency

The results of the questionnaire showed that 72% of farmers reported an increase in productivity after using digital advisory applications and simple soil sensors. The average increase in crop yield reaches 12% per planting season. Interviews with farmers in Cangkoak Village stated that the use of weather-based fertilizer recommendation applications helped reduce input costs by IDR 1.2 million per season. These findings support the literature showing that precision technology can improve outcomes while lowering costs (Getahun et al., 2024; Padhiary et al., 2024; Beach et al., 2025).

From observations, the use of pesticide spraying drones rented by the group was able to reduce working time from 6 hours to 1 hour per hectare, as well as reduce labor costs by up to 30%. Farmers state that the use of drones also reduces direct exposure to harmful chemicals. Similar studies in Southeast Asia confirm that drones not only improve the efficiency of input distribution, but also the aspect of occupational safety (Sarku et al., 2025; Ding et al., 2022; Lee et al., 2025).

However, productivity increases are not always linear. Some respondents reported that the growing season with extreme rainfall still lowered yields despite the use of technology. This confirms the results of research that climate change can limit the benefits of technology in the agricultural sector, especially in staple food commodities (Hu et al., 2024; Lobell et al., 2025; Hultgren et al., 2025).

In addition, the capital access factor also has an effect. Farmers with better financial ability can purchase additional sensors and subscribe to the app's premium features, while poor farmers only use the free features. An interview with an extension worker stated: *"Farmers with sufficient capital are more confident in trying new features, while poor farmers are more cautious for fear of loss."* This phenomenon is in accordance with the literature that shows that there is an inequality of benefits based on socio-economic class (Ingram et al., 2022; Ky et al., 2025; Rotz et al., 2019).

Other findings show that AgriTech also improves the efficiency of fertilizer use to 15% lower than traditional patterns. This supports studies that emphasize that digital technology is able to reduce nutrient runoff, maintain soil quality, and lower production costs (Anastasiou et al., 2023; Getahun et al., 2024; Canfield, 2024). Thus, AgriTech not only provides economic benefits, but also ecological benefits. However, the results of the interviews show that some farmers are still skeptical of weather application predictions because they are often not in accordance with field conditions. One farmer stated: *"The app says it's raining, but it's sunny here. So I trust my own experience more."* This is consistent with studies that emphasize the need to integrate technology with local wisdom to make it more acceptable to users (Van der Burg et al., 2019; Headey et al., 2024; Lee et al., 2024). Thus, the impact of AgriTech on productivity has proven to be positive, but the sustainability of its benefits is highly dependent on capital, weather, and social acceptance. For this reason, strengthening local capacity and contextual application design is key (Beach et al., 2025; Ding et al., 2022; Schulz et al., 2023).

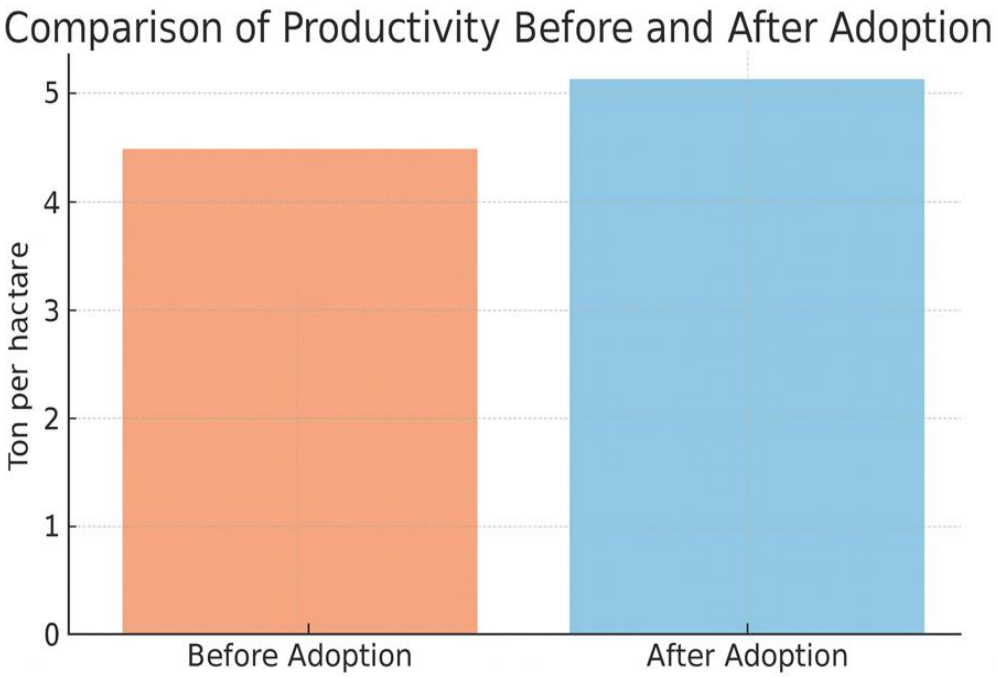

Figure 1. Comparison of Productivity Before and After AgriTech Adoption (Bar chart: before = 4.5 tons/ha; after = 5.1 tons/ha; average increase of 12%)

Description: The diagram shows the increase in average productivity, although the variation in yield between farmers is still significant.

Inclusion of Smallholders in Technology Access

While AgriTech brings tangible benefits, access to technology is uneven. The survey results show that 46% of farmers feel that the cost of subscription to the application is too high, 38% have difficulties with the internet network, and 33% have limited digital literacy. This is in line with *research* that confirms that economic and infrastructure barriers are the main factors inhibiting digital inclusion (Rotz et al., 2019; Canfield, 2024; Sarku et al., 2025). Observations show that farmers with larger plots of land are more willing to adopt the technology, while small, low-income farmers are often reluctant to try for fear of failure. One of the respondents stated: *"If you fail to*

harvest, you lose a lot. So I don't dare to try too many new technologies." This phenomenon is in line with research findings on the risks of technology adoption in the small agricultural sector (Ingram et al., 2022; Beach et al., 2025; Coggins et al., 2022).

In terms of gender, women are more active in using the market price feature than men. This shows that the application has the potential to strengthen women's bargaining positions in household economic decision-making. A similar study found that digital technology can reduce the gender gap in the agricultural sector when designed with women's needs in mind (Lowder et al., 2021; Atta-Aidoo et al., 2024; Herforth et al., 2025). However, the digital literacy gap is still very felt. Interviews with extension workers show that older farmers prefer direct explanations to reading application graphs. The extension worker stated: *"The application is good, but there must still be someone who bridges to the old farmers."* These findings are in line with the literature that confirms the need for blended extension (Ding et al., 2022; Lee et al., 2025; Beach et al., 2025).

Internet access is also a significant obstacle. In villages with a stable network, farmers are able to take advantage of the application features more optimally, while in villages with limited networks, the application only functions as a harvest record. This is in line with studies that affirm that the digital divide between urban and rural areas affects the distribution of technological benefits (Sarku et al., 2025; Canfield, 2024; Lee et al., 2024). In addition, observations found that farmers with community support were more likely to adopt technology. Farmer groups that regularly hold monthly meetings are quicker to understand the use of applications than individual farmers. The literature supports that local social and institutional factors play an important role in the success of innovation (Ingram et al., 2022; Rotz et al., 2019; Van der Burg et al., 2019).

Thus, the level of smallholder inclusion in AgriTech is strongly influenced by cost, infrastructure, digital literacy, and community support. Policy recommendations should focus on cost subsidies, network expansion, and digital literacy training so that the benefits of AgriTech are not only enjoyed by certain groups (Herforth et al., 2025; Headey et al., 2024; Ky et al., 2025).

Table 2. Barriers to AgriTech Access for Smallholder Farmers

Obstacles	Percentage (%)
High subscription fees	46
Limited internet network	38
Low digital literacy	33
Lack of training	29

Description: The table shows the main barriers to AgriTech adoption, confirming the need for policy interventions.

The Role of Extension Workers, Communities, and Local Institutions

The role of extension workers has proven to be very crucial in bridging farmers with digital technology. The results of the interviews show that the majority of farmers still rely on extension workers to understand application recommendations. The extension worker stated: *"Without guidance, farmers find it difficult to trust digital data."* These findings support studies confirming the effectiveness of blended extensions (Ding et al., 2022; Lee et al., 2025; Beach et al., 2025). Observations of farmer groups show that the use of drones and applications is more effective when done collectively. For example, farmer groups rent drones together so that costs are lower. This is in line with the literature that emphasizes the importance of collective institutions to strengthen access to technology (Hultgren et al., 2025; Lowder et al., 2021; Sarku et al., 2025). Local institutions such as village governments play a role in providing basic infrastructure. In villages with

village WiFi support, technology adoption is higher. Previous research has also emphasized the importance of local government support in reducing the digital divide (Canfield, 2024; Ky et al., 2025; Atta-Aidoo et al., 2024).

Interviews with representatives of app developers confirmed that they need local partners to make the app more accepted. They stated: *"It is difficult to go directly to farmers, so we cooperate with extension workers and village heads."* This is in line with the literature that emphasizes the importance of *co-design* technology with local actors (Ingram et al., 2022; Rotz et al., 2019; Van der Burg et al., 2019).

In addition, the local community also affects the speed of adoption. Farmer groups that have strong social ties are more likely to adapt to technology. Previous studies have found that social capital accelerates the adoption of innovation (Headey et al., 2024; Lee et al., 2024; Schulz et al., 2023). However, challenges arise when cultural resistance occurs. Some senior farmers refused to use the app because it was considered to be disrupting tradition.

Observations noted that there was a debate at farmer group meetings about dependence on technology. This is in line with studies that emphasize that cultural acceptance influences the success of technology (Hu et al., 2024; Coggins et al., 2022; Rotz et al., 2019). Thus, extension workers, communities, and local institutions are important pillars in ensuring that AgriTech is accepted and used effectively. Formal and informal institutional integration needs to be strengthened so that technology not only increases productivity, but also strengthens social cohesion (Ding et al., 2022; Ingram et al., 2022; Beach et al., 2025).

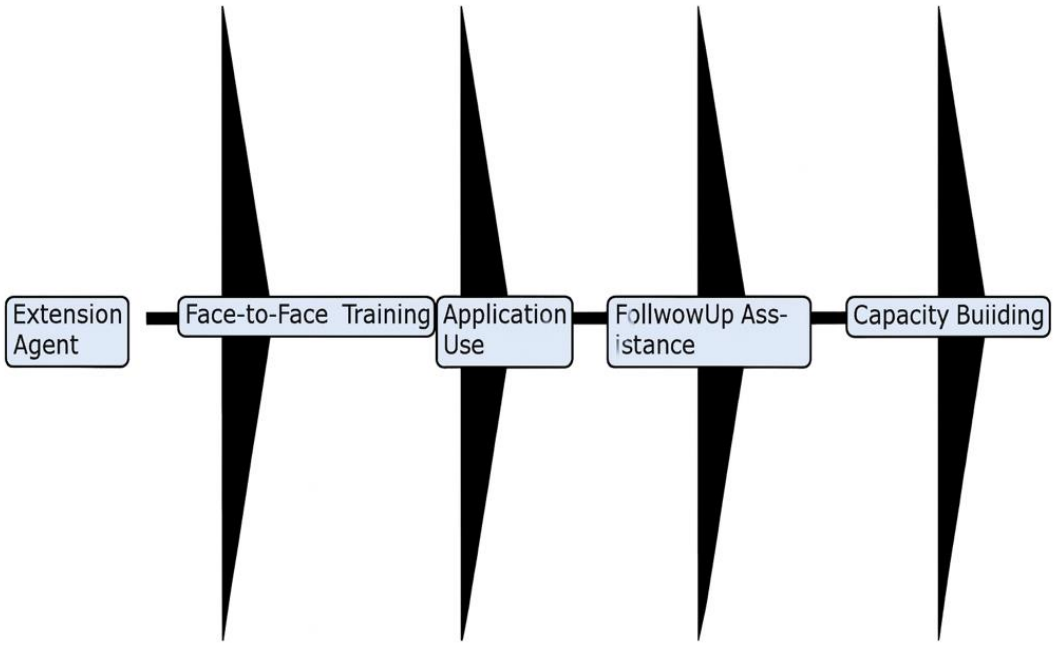

Figure 2. Blended Extension Scheme in AgriTech Adoption

Description: The image shows the combination of conventional and digital counseling creating a continuous learning cycle.

Implications for Food Security and Policy

The study found that AgriTech increases productivity, but has not fully addressed the issue of healthy food affordability. Interviews with women farmers confirmed that despite the increase in income, the price of animal protein is still difficult to reach. This is consistent with global data showing that more than 2.6 billion people cannot afford a healthy diet by 2024 (Herforth et al., 2025; Headey et al., 2024; World Bank, 2025). The implications of the need for policy interventions to ensure the benefits of AgriTech reach vulnerable groups. Data governance regulations, application fee subsidies, and the integration of fintech with digital advisories can strengthen inclusion. The literature confirms that without an inclusive regulatory framework, digital platforms can magnify inequality (Rotz et al., 2019; Canfield, 2024; Sarku et al., 2025).

Overall, this study confirms that the balance between technological efficiency and social inclusion is the key to sustainable food security. Innovation must be designed not only to increase crop yields, but also to ensure access and affordability of healthy food for all communities (Herforth et al., 2025; Headey et al., 2024; Atta-Aidoo et al., 2024).

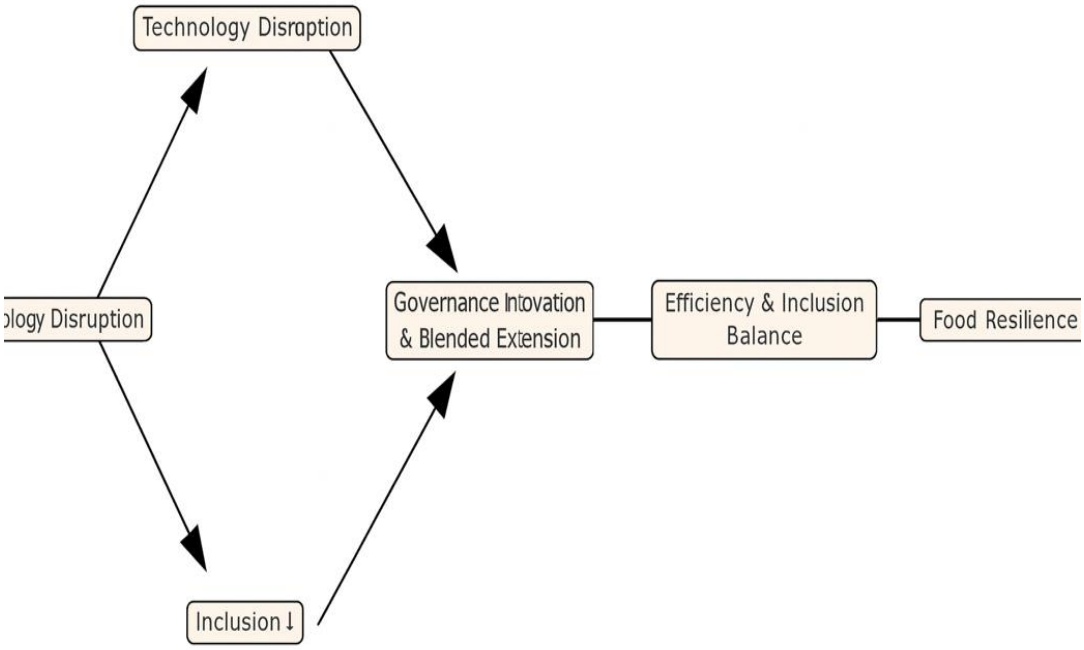

Figure 3. Trade-offs of Technology Disruption and Smallholder Inclusion
(Arrow: Technological Disruption → Agronomic Efficiency ↑, but Inclusion ↓; Governance Innovation & Blended Extension → Balance of Efficiency & Inclusion → Food Security ↑)

Description: The diagram confirms that the balance between efficiency and inclusion is a key requirement for the success of AgriTech innovation for food security.

CONCLUSION

This research proves that AgriTech increases the productivity and efficiency of smallholders with an average increase in crop yields of about 12% per season as well as a decrease in input costs. However, these benefits are not evenly distributed because there are still obstacles in the form of subscription fees, limited internet networks, and low digital literacy. Field findings confirm the trade-off between efficiency and inclusion, where technology provides agronomic benefits but has not yet fully reached all smallholders. To reduce this gap, blended extension models (a combination of face-to-face and digital counseling) and collective institutions have proven effective in driving wider adoption. In addition, the research emphasizes the importance of data governance and inclusive policies so that technological disruption does not widen inequality. Institutional innovations in the form of data regulation, application access subsidies, and the integration of fintech with digital advisories are the key to a balance between efficiency and justice. Overall, the study confirms that sustainable food security can only be achieved by balancing technological disruption and smallholder inclusion, so that innovation not only improves yields but also ensures healthy food affordability for all levels of society.

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