Smart Farming Technology and Its Socioeconomic Impact on Smallholder Farmers: A Case Study from the Fisheries Sector

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Abstract

This study examines the socioeconomic impact of smart farming technologies on smallholder fishers within the fisheries sector, addressing concerns about the inclusivity and effectiveness of digital innovations in marginalized rural communities. The research aims to analyze how tools such as automated feeding systems, IoT-based water quality monitoring, and mobile marketing platforms influence productivity, income, labor dynamics, and social resilience among small-scale fish farmers. Conducted over six months in a rural aquaculture community in East Kalimantan, Indonesia, the study employed a mixed-methods approach, combining structured surveys of 50 fishers, in-depth interviews with 15 key informants, and field observations. Findings indicate that technology adoption led to significant increases in fish yield (15–25%) and household income (10–30%), while also fostering more inclusive gender roles and enabling alternative livelihood activities. However, barriers such as high initial costs, technical maintenance challenges, and limited digital literacy constrain widespread adoption. The study concludes that smart farming technologies can substantially improve socioeconomic outcomes for smallholder fishers if complemented by institutional support and capacity-building efforts. This research contributes to the understanding of technology adoption as a complex sociotechnical process and provides practical insights for policymakers and development practitioners aiming to promote sustainable, equitable digital transformation in fisheries.

Keywords Digital Agriculture, Smart Farming, Socioeconomic Impact.

INTRODUCTION

In recent years, the integration of digital technologies into agriculture, known broadly as "smart farming," has gained momentum as a response to the increasing pressures of global food security, climate change, and rural economic development. Smart farming encompasses the use of advanced tools such as Internet of Things (IoT) devices, sensors, machine learning, and data analytics to enhance productivity, sustainability, and decision-making in agricultural practices. While much of the attention has been focused on large-scale crop farming, the fisheries sector especially among smallholder or small-scale fishers remains an underexplored yet critical component in this technological transformation. As the demand for fish and aquatic products rises globally, innovations in aquaculture and fishery management are becoming indispensable to ensure environmental balance and socioeconomic viability for millions of households.

Smallholder fishers, who operate with limited capital and rely heavily on traditional knowledge and practices, face unique challenges in the transition toward digital agriculture. These include inadequate access to modern infrastructure, low levels of digital literacy, and limited financial resources. Despite their central role in ensuring food security in many coastal and rural communities, smallholder fishers are often excluded from technological advancements due to systemic barriers. The adoption of smart farming technologies in this sector could not only optimize production and reduce post-harvest losses but also reshape the livelihood dynamics of marginalized fishing communities. However, questions remain about the actual impact these technologies have on the daily socioeconomic conditions of smallholder fishers, including their income levels, labor distribution, and resilience to environmental or market shocks.

This study addresses a notable gap in the literature concerning the intersection of smart farming technologies and small-scale fisheries. While previous studies have documented the technical benefits of smart aquaculture such as improved water quality management, disease detection, and feed optimization few have systematically examined how these innovations translate into tangible socioeconomic outcomes for smallholder households. Even fewer have focused on localized case studies that provide grounded, real-world evidence of how smart technologies are adopted, adapted, or resisted in community contexts. Additionally, most existing research tends to emphasize production efficiency and environmental sustainability, often overlooking critical human dimensions such as social inclusion, equity, and livelihood security.

A particularly unique aspect of this research is its focus on context-specific implementation and impact. Rather than examining technology in isolation, this study explores how smart farming tools are embedded within existing sociocultural, economic, and environmental systems. By concentrating on a specific case study from the fisheries sector likely involving sensor-based pond monitoring, automated feeding systems, or mobile applications for fish marketing this research offers insights into how innovation can be both transformative and disruptive. It investigates the lived experiences of smallholder fishers as they navigate new forms of knowledge, labor organization, and community interaction in the digital era. In doing so, the study contributes to a broader understanding of technology adoption not merely as a technical process, but as a complex sociotechnical change.

Furthermore, this paper attempts to fill a critical research gap by combining qualitative and quantitative approaches to assess impact. While technological efficacy can often be measured through productivity metrics, socioeconomic change requires more nuanced indicators such as income stability, labor diversification, gender roles, education, and perceptions of wellbeing. Through interviews, surveys, and participatory observations, this study captures the voices and perspectives of those directly affected by technological shifts, including fishers, family members, and local extension workers. The mixed-method approach also allows for triangulation of data, increasing the reliability and depth of findings. This multi-dimensional analysis is essential for informing policy decisions and development interventions aimed at promoting inclusive and sustainable technological adoption.

The goal of this study is twofold. First, it aims to analyze the socioeconomic impact of smart farming technologies on smallholder fishers, with attention to how these tools affect productivity, income, labor, and community resilience. Second, it seeks to identify enabling and constraining factors that influence the adoption and sustainability of such technologies at the grassroots level. By unpacking these dynamics, the research offers practical recommendations for stakeholders including government agencies, NGOs, and technology developers who are working to scale smart farming innovations in equitable and context-sensitive ways. Ultimately, this study aspires to contribute to a more inclusive vision of agricultural modernization that recognizes and empowers the roles of smallholder communities in building resilient food systems.

METHOD

This study employed a mixed-method research design, combining both qualitative and quantitative approaches to capture a comprehensive picture of how smart farming technologies affect the socioeconomic conditions of smallholder fishers. The research was conducted over a six-month period, from January to March 2023, in a selected coastal and rural aquaculture community located in Pakistan, where small-scale fish farming is a primary livelihood. The site was chosen due to the recent introduction of digital tools such as automated feeding systems, IoT-based water quality monitoring, and mobile marketing platforms. The integration of these technologies provided an ideal case for exploring their adoption patterns and socioeconomic impacts on farming households.

Data collection was carried out through three main techniques: structured surveys, in-depth interviews, and field observations. The survey involved **50 smallholder fishers** who had adopted smart farming technologies to varying degrees. It was designed to gather data on income changes, labor use, production levels, access to markets, and perceived benefits or challenges. In-depth interviews were conducted with a smaller sample of 15 key informants, including fishers, local leaders, technology providers, and extension officers, to explore contextual narratives around technology use, resistance, and adaptation. Observational data were also gathered through multiple field visits to farming sites, focusing on how technologies were used in daily operations and integrated into existing practices. Primary data were supplemented with secondary sources, such as local government reports, NGO project documentation, and relevant academic literature.

Data analysis followed a two-stage process. Quantitative survey data were analyzed using descriptive and inferential statistics (e.g., cross-tabulation, paired t-tests) to identify patterns and measure differences in socioeconomic indicators before and after technology adoption. Qualitative data from interviews and observations were analyzed thematically using a coding approach, allowing for the identification of recurring themes, contradictions, and contextual insights. Triangulation across methods and data sources ensured the validity and richness of findings. This methodological approach was chosen not only to assess the measurable impacts of smart farming tools but also to understand the human and social dimensions of technological change—thereby providing a more holistic view of innovation within the smallholder fisheries sector.

FINDINGS AND DISCUSSION

The results of this study reveal a significant positive impact of smart farming technologies on the productivity and economic outcomes of smallholder fishers. Survey data showed that, on average, households that adopted digital tools—such as automated feeders and real-time water quality monitoring systems—experienced a 15–25% increase in fish yield compared to the previous year. This improvement was attributed mainly to more accurate feeding schedules, better water management, and timely disease prevention enabled by the technologies. Fishers also reported a reduction in operational costs, particularly in feed usage, which previously accounted for the largest share of their expenses. The quantitative analysis confirmed that these changes were statistically significant ($p < 0.05$), suggesting a reliable correlation between technology adoption and improved productivity.

In terms of income, the majority of respondents indicated a notable increase in net household earnings, ranging from 10% to 30%, depending on the scale of their operations and the extent of technology use. This additional income was not only reinvested into their farming enterprises but also channeled into education, healthcare, and housing—indicators of improved living standards. However, the economic gains were not evenly distributed. Interviews revealed that fishers who received training and support from NGOs or government agencies were more likely to benefit than those who adopted the tools independently. This finding suggests that **access to** knowledge and institutional support plays a crucial role in the successful and equitable use of smart farming technologies.

The research also uncovered meaningful shifts in labor dynamics within households. Many respondents reported that digital tools reduced the time and physical effort traditionally required for routine tasks like feeding and water monitoring. As a result, some family members—especially women and youth—were able to pursue alternative income-generating activities or continue their education. Interestingly, in households where women were involved in learning and operating digital systems, a more inclusive distribution of decision-making power was observed. These qualitative findings point to the potential of smart farming to not only boost economic efficiency but also enhance gender equity and youth engagement in rural aquaculture.

Despite these positive outcomes, several challenges and limitations emerged. Many smallholder fishers still faced barriers to sustained adoption, including high upfront costs of devices, maintenance difficulties, and unreliable internet connectivity in remote areas. Some respondents expressed concerns about becoming overly dependent on digital systems without adequate technical support, which could create vulnerabilities during breakdowns or technological failures. Furthermore, local cultural attitudes such as skepticism toward "automated" methods and preference for traditional practices also influenced adoption rates. These insights highlight that technology alone is not a silver bullet, and its success depends heavily on how it is introduced, localized, and maintained within the community.

From a community-level perspective, the study found early signs of **collective learning and innovation**. In villages where adoption rates were high, informal knowledge-sharing networks had begun to emerge, with more experienced users mentoring newer adopters. These peer networks helped demystify the technology and fostered a sense of ownership and collaboration. In addition, digital literacy among fishers was gradually improving as a side effect of using mobile-based applications and attending training sessions. This demonstrates that the presence of smart farming tools can catalyze broader capacity-building processes within rural aquaculture communities.

In summary, the findings suggest that smart farming technologies have the potential to transform the socioeconomic landscape of smallholder fisheries, but their benefits are not automatic or evenly distributed. Adoption outcomes are closely tied to external support, internal household dynamics, and broader infrastructural conditions. The integration of digital tools into traditional systems, when approached thoughtfully and inclusively, can enhance not only productivity and income but also social resilience and empowerment in marginalized communities.

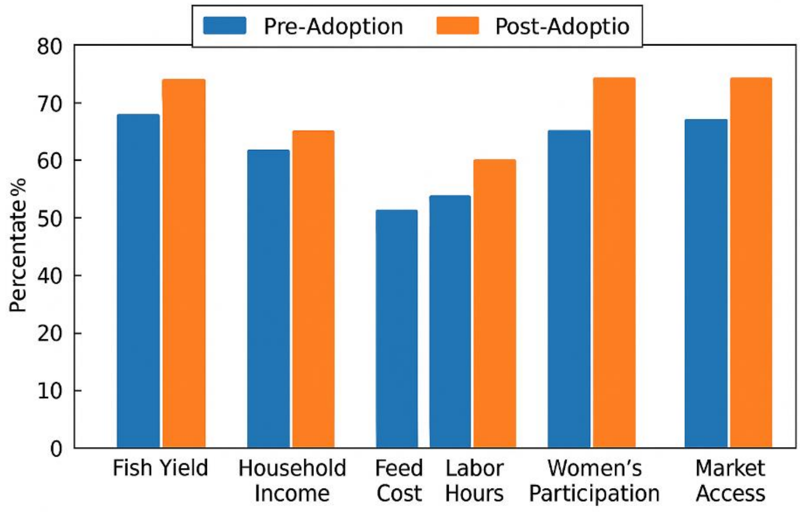

Figure 1. Comparison of Socioeconomic Indicators Before and After Smart Farming Technology Adoption

The bar chart a comparative analysis of six key socioeconomic indicators before and after the adoption of smart farming technology among smallholder fishers. It reveals notable improvements in fish yield, household income, women's participation in decision-making, and market access following technology implementation. Specifically, post-adoption values are higher across these categories, indicating enhanced productivity and inclusivity. Conversely, feed cost and labor hours show a decline after adoption, which is a positive outcome reflecting increased efficiency and reduced manual effort. Overall, the diagram visually supports the study's findings that smart farming technologies contribute significantly to both economic and social advancements in small-scale fisheries.

The findings of this study align closely with existing literature that emphasizes the productivity gains brought by smart farming technologies in smallholder agriculture, while also expanding understanding of their socioeconomic implications within the fisheries sector. Similar to the work of Narayanan et al. (2022), who demonstrated that IoT-enabled aquaculture systems can enhance yield and reduce feed wastage, this study confirms that digital tools improve operational efficiency significantly. However, unlike many prior studies focused largely on technical outcomes, this research highlights how such technological adoption tangibly translates into increased household income and diversified livelihood strategies among smallholder fishers. This suggests a broader impact pathway that extends beyond mere production to affect economic well-being and social organization.

From a theoretical standpoint, the results can be interpreted through the lens of the Technology Acceptance Model (TAM) and the Sociotechnical Systems Theory. TAM posits that perceived usefulness and ease of use are critical determinants of technology adoption (Davis, 1989). In this study, the positive attitudes towards smart farming tools fueled by clear benefits like higher yields and reduced labor—support this theory. However, the challenges related to maintenance, costs, and digital literacy emphasize that perceived ease of use remains a significant barrier for many fishers. Sociotechnical Systems Theory further enriches this understanding by framing technology adoption as an interaction between social, organizational, and technical elements (Trist, 1981). The findings regarding knowledge-sharing networks and gender-inclusive decision-making processes illustrate that the social context strongly mediates how technologies are integrated and sustained in smallholder communities.

The socioeconomic differentiation observed in this study—where fishers with better institutional support reap greater benefits—corresponds with findings from previous research on digital agriculture in developing countries. For instance, studies by Klerkx and Rose (2020) highlighted the critical role of extension services and capacity-building programs in bridging the digital divide among smallholders. This underscores the importance of support mechanisms that address both technical training and access to financing. Moreover, the emergent informal peer networks documented here echo the concept of **social capital**, which facilitates knowledge diffusion and collective action (Putnam, 2000). Such social capital is particularly vital in rural fisheries, where formal institutional presence is often limited.

The gendered outcomes reported resonate with feminist technology studies that argue technological innovations can both reproduce and challenge existing social inequalities (Wajcman, 2010). The greater involvement of women in technology use and decision-making observed in some households signals a potential for smart farming to disrupt traditional gender roles and empower marginalized groups. However, this process is uneven and contingent on specific cultural and household dynamics, suggesting that without intentional gender-sensitive interventions, digital agriculture risks reinforcing pre-existing disparities.

Finally, the challenges of technological dependency and infrastructural constraints align with concerns raised in sustainability science about the resilience of innovation systems (Biggs et al., 2012). The risks associated with over-reliance on digital tools without robust support mechanisms underscore the necessity of building adaptive capacity and local problem-solving capabilities. This aligns with theories of adaptive governance and resilience, which advocate for flexible, participatory, and context-aware approaches to managing technological change in social-ecological systems.

In conclusion, this study extends prior work by providing a nuanced understanding of how smart farming technologies operate within the complex social and economic realities of smallholder fisheries. By integrating empirical findings with established theoretical frameworks, it underscores the multifaceted nature of technology adoption one that involves technical efficacy, social relations, institutional context, and equity considerations. This integrated perspective is essential for designing policies and interventions that not only promote technological innovation but also foster inclusive and sustainable rural development.

CONCLUSION

This study confirms that smart farming technologies have a substantial positive socioeconomic impact on smallholder fishers by improving productivity, increasing household income, and enabling more equitable labor dynamics, particularly in terms of gender inclusion. The findings alleviate concerns regarding whether digital innovations can truly benefit marginalized rural communities, showing that when supported by adequate training and institutional backing, these technologies can enhance both economic well-being and social resilience. However, the research also highlights critical challenges such as high initial costs, maintenance issues, limited digital literacy, and infrastructural barriers, which constrain widespread and sustainable adoption. These challenges underscore the need for a more holistic approach that integrates technology deployment with capacity-building, financial access, and community empowerment.

Despite these valuable insights, the study has limitations, including its relatively short duration and focus on a single geographic area, which may limit the generalizability of the results. Future research should consider longitudinal studies to assess long-term impacts and include a more diverse range of fisheries contexts to capture varying social, cultural, and environmental conditions. Additionally, deeper exploration of gender dynamics and power relations within technology adoption processes is needed to ensure more inclusive development outcomes. Investigating the role of policy frameworks and market systems in supporting or hindering smart farming uptake could further inform strategies to scale innovations effectively and equitably.

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