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Harnessing Smart Farming: Key Determinants of Automated Mini Greenhouse Adoption and Use in the Philippines

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ABSTRACT: This research investigated the determinants of adopting and sustaining the utilization of automated mini-greenhouses in the Philippines, a nation particularly vulnerable to climate change. Using an integrated theoretical framework combining the Unified Theory of Acceptance and Use of Technology (UTAUT2), Diffusion of Innovation (DOI), and Actor-Network Theory (ANT), this research employed a quantitative approach to assess key constructs, such as performance expectancy, effort expectancy, social influence, facilitating conditions, hedonic motivation, trust, habit, and technology readiness. Data were collected through structured surveys administered to smallholder farmers, and the results were analyzed using Python-based statistical tools. The findings indicated that performance expectancy and social influence were significant predictors of technology adoption, while habit and facilitating conditions strongly influenced continued use. Trust and resource accessibility, derived from DOI and ANT, also emerged as critical factors in sustained utilization. These results contributed to understanding smart farming adoption in the context of climate resilience and sustainable agriculture. Future research should explore broader applications of such technologies and further examine their long-term sustainability.

KEYWORDS: Automated mini-greenhouse; technology adoption; UTAUT 2; intention to use; smart agriculture

1. Introduction

Agriculture in the Philippines faces increasing challenges due to the effects of climate change, including extreme weather events, fluctuating temperatures, and erratic rainfall patterns. As a predominantly agricultural economy, these issues threaten the livelihoods of millions of smallholder farmers, who constitute a significant portion of the rural population. According to the Global Climate Risk Index, the Philippines ranks among the most vulnerable countries to climate-related risks, highlighting the urgency of developing adaptive and sustainable agricultural solutions [1].

Smart farming technologies, including automated systems, offer promising solutions to these challenges. Among these innovations, automated mini-greenhouses stand out for their ability to optimize growing conditions, shield crops from adverse weather, and ensure year-round food production. Equipped with sensors that monitor temperature, humidity, and soil moisture, these systems enable precise environmental control, potentially enhancing agricultural productivity and sustainability. However, adoption rates remain low despite their potential, particularly in rural areas where resource constraints and technological unfamiliarity prevail [2].

Existing studies on technology adoption, such as the work by Venkatesh et al. [3], have utilized frameworks like UTAUT2 to identify determinants such as performance expectancy, effort expectancy, and social influence. Michels et al. [3] explored the adoption of alternative fuel tractors in German agriculture, applying UTAUT2 and identifying the critical role of environmental and contextual factors. Similarly, Min et al. [4] examined the adoption of sensor and robotic technologies in China's greenhouse sector, emphasizing the importance of tailoring technology promotion to diverse stakeholder preferences. These studies highlight the need for localized approaches and consideration of stakeholder-specific factors but often neglect rural settings in climate-vulnerable regions. This study aims to fill this gap by investigating the determinants of adoption and sustained utilization of automated mini-greenhouses among smallholder farmers in the Philippines.

Furthermore, Wang et al. [5] investigated end-user acceptance of intelligent decision-making in digital agriculture, identifying trust as a critical determinant. Osrof et al. [6] conducted a systematic review on smart farming adoption, proposing a future agenda to address challenges such as digital literacy and infrastructure gaps. Additional research has highlighted the economic and environmental effects of smart farming technologies [7], the barriers to Agriculture 4.0 adoption [8], and the challenges in scaling agricultural robotics [9]. Despite these valuable insights, gaps remain in integrating alternative frameworks such as DOI and ANT into behavioral models like UTAUT2, particularly in rural, climate-vulnerable regions.

While UTAUT2 offers valuable insights into technology adoption, integrating additional theoretical perspectives like DOI and ANT can provide a more comprehensive analysis. DOI emphasizes the role of early adopters, social influence, and the compatibility of innovations with existing practices, which are crucial factors for understanding how and why farmers in rural communities might embrace new technologies. By considering the social networks and community dynamics within which farmers operate, DOI enriches our understanding of adoption behaviors [10]. On the other hand, ANT explores the interactions between humans and non-human actors (such as technology, policies, and the environment), helping to explain how the broader infrastructure, resource availability, and the dynamics between farmers and technology influence the integration of automated mini-greenhouses [11]. Figure 1 illustrates the integration of UTAUT2, DOI, and ANT, showing how behavioral, adoption, and relational factors converge to influence the adoption and sustained use of automated mini-greenhouses.

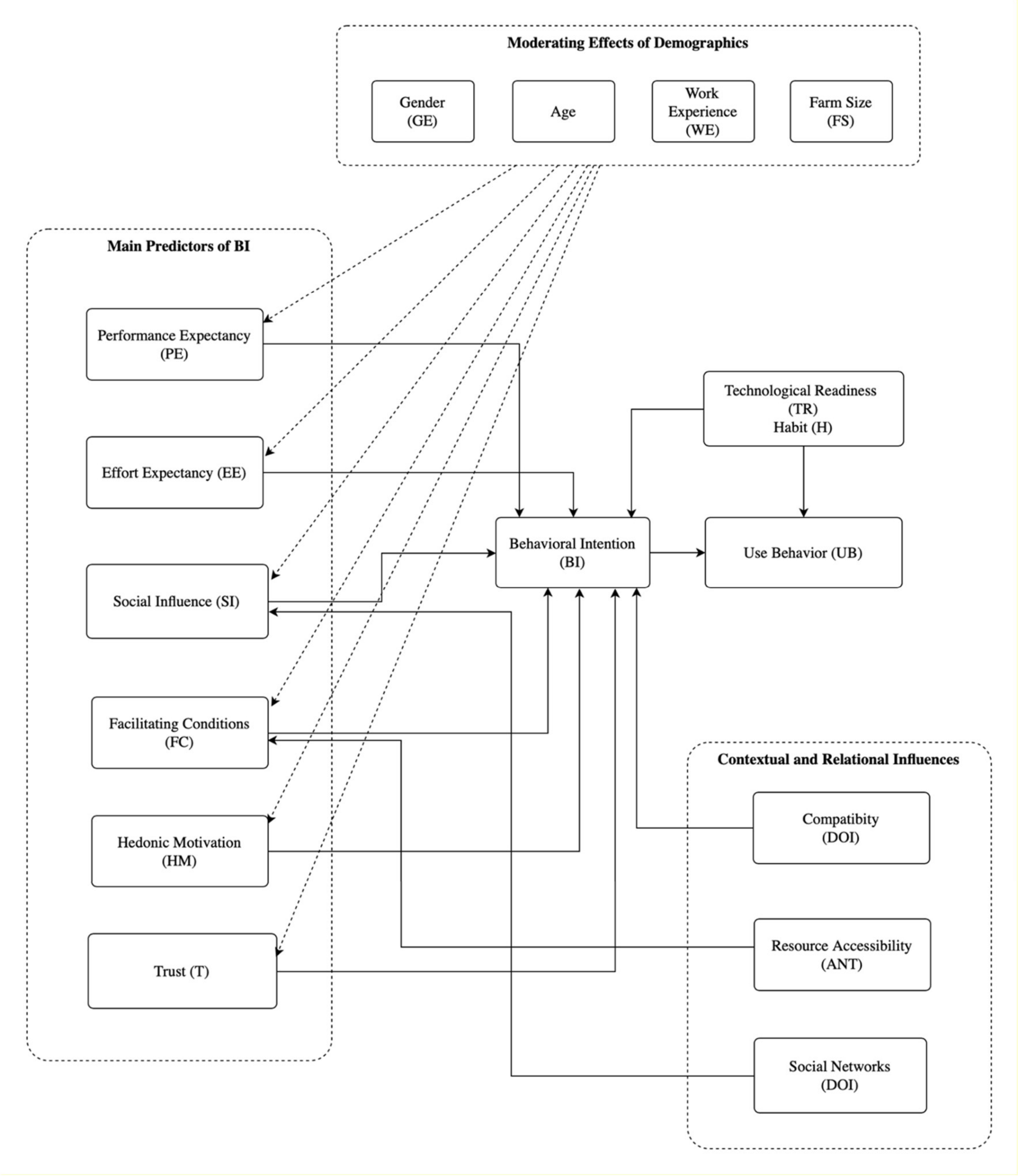

Figure 1. Conceptual Framework (UTAUT2, DOI, and ANT Integration).

This research integrates trust and technological readiness into the UTAUT2 framework to comprehensively understand farmers' behavioral intentions and usage behaviors. Trust and technological readiness emerge as key predictors of adoption and continued use [12]. Trust fosters confidence in the technology's reliability, while technological readiness ensures that farmers feel equipped to adopt the innovation. By addressing both the technological and relational dimensions of adoption, this study offers a comprehensive framework for promoting sustainable agricultural practices and enhancing climate resilience. Moreover, this research contributes to the broader discourse on sustainable agriculture and climate resilience by addressing these dimensions and providing actionable insights for stakeholders, including policymakers, agricultural extension workers, and technology developers. Additionally, the study highlights the critical role of integrating behavioral, adoption, and relational factors, bridging existing theoretical gaps, and offering practical solutions to improve technology uptake and sustainability. Building on this framework, this study aims to investigate the factors influencing the acceptance and continued utilization of automated mini-greenhouses in the Philippines. Specifically:

1. To ascertain the principal factors influencing the adoption of automated mini-greenhouses.
2. To identify the key factors that facilitate the sustained utilization of the technology.

Based on the integration of the UTAUT2, DOI, and ANT frameworks, the following hypotheses are proposed:

H1: Perceived efficacy of a technology is a significant predictor of intention to use (UTAUT2).

- H1a: Demographic factors such as gender, age, work experience, and farm size affect the strength of the relationship between perceived efficacy and intention to use the technology (UTAUT2).

H2: Effort expectancy regarding technology utilization significantly influences the intention to adopt it (UTAUT2).

- H2a: Demographic characteristics, including age and experience, influence the perception of effort expectancy and its relationship with behavioral intention (UTAUT2).

H3: Social influences, including peer pressure and endorsements from others, significantly affect the intention to use the technology (UTAUT2, DOI).

- H3a: Demographic factors may moderate the impact of social influence on the intention to adopt the technology (UTAUT2, DOI).

H4: The accessibility of resources and infrastructure essential for utilizing a technology significantly influences its adoption (ANT, DOI).

- H4a: Demographic considerations may influence the relationship between resource availability and the adoption of technology (ANT, DOI).

H5: The delight received from utilizing a technology substantially influences the intention to use it.

- H5a: The impact of pleasure or enjoyment obtained from utilizing a technology on the intention to employ it may be affected by demographic variables.

H6: Established routines or habits profoundly influence the desire to utilize a technology.

- H6a: Demographic considerations may moderate the impact of existing routines or habits on the desire to utilize a technology.
- H6b: Established routines or habits substantially influence the actual utilization of a technology.

H7: The degree of trust in the technology provider or the technology itself profoundly influences the desire to utilize it UTAUT2, ANT).

- H7a: Demographic characteristics may moderate the impact of trust on the intention to utilize a technology.

H8: The perceived efficacy of individuals in utilizing a technology substantially influences their intention to use it.

- H8a: Demographic considerations may mitigate the impact of perceived technological proficiency on the intention to utilize the technology.

  The perceived capability to utilize a technology strongly influences its actual usage.

H9:The intentions of individuals to utilize a technology considerably influence their actual usage of that technology.

- H9a: Demographic characteristics, including gender, age, work experience, and farm size, may modify the association between the intention to utilize and the actual use of a technology.

2. Materials and Methods

This study employed a quantitative research design to examine the determinants of adoption and sustained utilization of automated mini-greenhouses for smart agriculture in the Philippines. The Unified Theory of Acceptance and Use of Technology (UTAUT2) framework served as the primary theoretical foundation, supplemented by the DOI and ANT frameworks. UTAUT2 modeled behavioral intentions and technology usage behavior, while DOI and ANT provided insights into contextual, relational, and compatibility factors influencing adoption and sustained use. Data were collected using a structured survey instrument and analyzed with Python-based statistical tools.

2.1 Materials.

The study utilized the following materials:

- Survey Instrument: A structured questionnaire was developed, comprising two main sections:
  1. UTAUT2 constructs, including performance expectancy, effort expectancy, social influence, facilitating conditions, hedonic motivation, habit, trust, and technology readiness, were evaluated on a five-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree).
  2. Demographic information includes age, gender, farm size, and agricultural experience.
- Data Analysis Software: Python 3.8 was employed for statistical analysis. Key libraries included Pandas (data manipulation), Scikit-learn (regression analysis), and Matplotlib/Seaborn (visualization).

2.2 Participants.

The study targeted 100 smallholder farmers from Northern Luzon, Philippines, who are significantly affected by climate variability. A purposive sampling technique ensured the inclusion of participants with relevant experience or interest in automated greenhouse technology. The sample's demographic diversity—considering age, gender, farm size, and agricultural expertise—enabled a robust analysis of moderating variables.

2.3 Data collection procedure

The data collection process was carefully designed to ensure the study's reliability and ethical integrity. Surveys were conducted in person with the assistance of trained enumerators to facilitate participant comprehension. Each session lasted approximately 30 minutes, during which enumerators provided clarifications as needed to ensure accurate responses. Before full survey administration, the questionnaire was pretested on a small sample of 10 farmers to evaluate its clarity and reliability. This pilot testing led to minor adjustments in phrasing, enhancing the overall quality of the instrument. Ethical protocols were rigorously followed throughout the study. Approval was obtained from the institutional review board (REC Code: 03162023-091), and informed consent was secured from all participants before data collection. Anonymity was guaranteed, and participants were assured of their right to withdraw from the study at any time, safeguarding their autonomy and confidentiality.

2.4 Experimental design.

The study was non-experimental and observational, focusing on farmers' self-reported behaviors and perceptions regarding automated mini greenhouses. The primary variables included:

- Independent Variables: UTAUT2 constructs and demographic factors.
- Dependent Variables: Behavioral intention and usage behavior.

Integrating the DOI and ANT frameworks was employed to enhance understanding of the contextual and relational dynamics influencing the adoption and sustained utilization of automated mini-greenhouses. DOI focused on compatibility with existing practices and the role of early adopters, while ANT examined the interplay between human and non-human actors (e.g., technology, policies, and environmental factors).

2.5 Data analysis.

The data analysis involved several steps to examine the research constructs thoroughly. Descriptive statistics, including central tendencies (mean, median) and variability (standard deviation), were calculated to overview the UTAUT2 constructs comprehensively. Correlation analysis was then conducted using Pearson correlation coefficients to identify relationships among these constructs. Multiple linear regression models were applied to assess the predictive strength of the independent variables on behavioral intention and usage behavior. Additionally, the analysis incorporated moderation effects by evaluating interaction terms for demographic variables. In cases where data was unavailable, theoretical results were integrated based on the frameworks' postulations to infer potential relationships and outcomes. This approach ensured consistency with the study's conceptual framework.

2.6 *Ethical considerations.*

The research adhered to ethical guidelines, ensuring the study's design and implementation prioritized participant welfare. A detailed informed consent process was conducted, including an explanation of the study's purpose and confidentiality assurances. Ethical approval was obtained from the institutional review board before commencing data collection.

2.7 Limitations.

The study's reliance on self-reported data introduces the potential for response bias. Theoretical interpretations were used where data was unavailable, which may limit empirical validation. Future research could incorporate longitudinal designs to mitigate this limitation and provide insights into behavioral changes.

3. Results and Discussion

A total of 100 respondents participated, representing a diverse group of smallholder farmers. Table 1 summarizes the descriptive statistics for key constructs, including performance expectancy (PE), effort expectancy (EE), social influence (SI), facilitating conditions (FC), hedonic motivation (HM), trust (T), technology readiness (TR), habit (H), behavioral intention (BI), and use behavior (UB).

Table 1. Descriptive statistics of UTAUT2 constructs.

Construct	Mean	SD	Skewness	Kurtosis
Performance Expectancy (PE)	3.318	0.811	-0.738	-0.789
Effort Expectancy (EE)	2.998	0.896	-0.475	0.649
Social Influence (SI)	3.63	0.903	-0.527	0.771
Facilitating Conditions (FC)	3.492	0.961	-0.388	0.293
Hedonic Motivation (HM)	3.704	1.062	-0.665	-0.09
Trust (T)	3.693	1.04	-0.648	-0.522
Technological Readiness (TR)	3.247	1.256	-0.76	0.591
Habit (H)	3.318	1.265	-0.837	0.625
Behavioral Intention (BI)	3.601	1.32	-1.177	1.054
Use Behavior (UB)	3.509	1.307	-1.153	1.109

Table 2. Correlation Matrix

	UT	PE	EE	SI	FC	HM	PV	T	TR	H	BI	UB	GE	AGE	ED	WE	LC
UT	1																
PE	0.34	1															
EE	-0.04	0.35	1														
SI	0.37	0.75	0.36	1													
FC	0.19	0.63	0.35	0.7	1												
HM	0.3	0.81	0.39	0.76	0.72	1											
PV	0.22	0.85	0.36	0.75	0.67	0.83	1										
T	0.19	0.83	0.35	0.75	0.69	0.82	0.88	1									
TR	0.26	0.67	0.27	0.6	0.59	0.69	0.65	0.81	1								
H	0.28	0.66	0.28	0.65	0.63	0.71	0.64	0.81	0.92	1							
BI	0.21	**0.73**	0.25	**0.63**	**0.57**	**0.73**	**0.69**	**0.81**	**0.86**	**0.89**	1						
UB	0.11	**0.69**	0.28	**0.57**	**0.56**	**0.7**	**0.68**	**0.81**	**0.83**	**0.85**	**0.9**	1					
GE	0.11	-0.07	-0.06	0	0.02	0	-0.06	-0.02	0.04	0.06	-0.02	0	1				
AGE	-0.68	-0.22	0.08	-0.22	-0.05	-0.18	-0.09	-0.06	-0.16	-0.13	-0.13	-0.03	-0.16	1			
ED	0.32	0.26	0.06	0.28	0.2	0.21	0.24	0.21	0.25	0.21	0.17	0.15	-0.04	-0.31	1		
WE	-0.48	-0.22	0.09	-0.15	-0.11	-0.2	-0.14	-0.1	-0.15	-0.12	-0.13	-0.05	-0.11	0.64	-0.11	1	
LC	-0.4	-0.08	0.07	-0.1	0.02	-0.02	-0.05	-0.04	-0.02	-0.04	-0.09	0	0.11	0.26	0.01	0.25	1

Moderate Positive - BI: FC
UB: SI, FC,
Strong Positive - BI: PE, SI, HM, PV
UB: PE, HM, PV
Very Strong Positive - BI: T, TR, H, UB
UB: T, TR, H, BI

3.1. Results

3.1.1 Adoption predictors.

Pearson correlation analysis identified trust (r = 0.81), technology readiness (r = 0.83), and habit (r = 0.85) as the strongest positive predictors of adoption. These findings align with the DOI framework, which emphasize compatibility and trialability as key factors in technology adoption. Performance expectancy (r = 0.69), hedonic motivation (r = 0.70), and price value (r = 0.68) also significantly influenced use behavior, consistent with DOI's focus on relative advantage. Social influence (r = 0.57) underscores the role of early adopters in promoting adoption, while facilitating conditions (r = 0.56) highlight the importance of non-human actors, as described in ANT. Effort expectancy showed a weak positive correlation (r = 0.52), suggesting that ease of use plays a secondary role. These relationships are visually summarized in Table 2, which presents the correlation matrix for all measured constructs.

3.1.2 Sustained utilization predictors.

BI, strongly influenced by trust (r = 0.81), technology readiness (r = 0.86), and habit (r = 0.89), emerged as the primary predictor of sustained usage. This supports ANT's emphasis on stable networks of human and non-human actors in ensuring continued use. Performance expectancy (r = 0.73), hedonic motivation (r = 0.73), and social influence (r = 0.63) were also significant contributors, highlighting the importance of perceived benefits and community dynamics. Facilitating conditions moderately impacted BI (r = 0.57), while effort expectancy had minimal effect, reinforcing the notion that established routines reduce perceived complexity.

3.2. Discussion.

The study demonstrates that intrinsic motivators—trust, technology readiness, and habit—are critical for both adopting and sustaining automated mini-greenhouses. From the DOI framework perspective, these findings highlight that the perceived compatibility of automated mini-greenhouses with farmers' current practices and their relative advantage (e.g., improved productivity and resilience) drive adoption. Trust fosters confidence in the system's reliability, while technological readiness ensures farmers feel equipped to integrate innovation into their routines. Habit reflects the successful assimilation of technology into daily farming practices, emphasizing long-term sustainability. Insights from ANT further reveal the importance of both human actors (e.g., farmers and community leaders) and non-human actors (e.g., greenhouse systems, infrastructure, and policies) in fostering adoption. Facilitating conditions, such as access to reliable resources and technical support, act as critical nodes in the actor network. Trust strengthens these connections, ensuring network stability and encouraging continued use.

3.2.1 Policy implications.

Addressing adoption barriers and ensuring sustained use requires actionable strategies:

- Subsidies and Financial Incentives**:** Policymakers should alleviate the financial burden of adoption by providing targeted subsidies, particularly for smallholder farmers. Lowering upfront costs can enhance the perceived relative advantage, a core principle of DOI.
- Capacity Building**:** Training programs that build technological readiness are essential. Farmers must be equipped with the skills to operate automated greenhouses effectively. Demonstrations or trial programs can help build trust and ensure compatibility with existing practices, as emphasized by DOI's focus on trialability.
- Community-Based Promotion**:** Leveraging social influence through endorsements from early adopters or community leaders can amplify technology's perceived benefits. This aligns with DOI's emphasis on the role of communication channels in diffusion.
- Infrastructure Development**:** Investments in robust infrastructure and technical support address the ANT perspective by strengthening the role of non-human actors. Reliable connectivity and maintenance services are vital for long-term usability.

3.2.2 Contribution to existing research.

This study extends the UTAUT2 framework by integrating DOI and ANT, providing a comprehensive understanding of adoption in rural, climate-vulnerable contexts. The strong influence of trust and habit aligns with prior findings by [5] and [6] regarding their global relevance. The novel application of ANT highlights the critical role of infrastructure, policies, and technology in fostering stable networks that support adoption and sustained use.

3.2.3 Limitations and future research.

The study's reliance on self-reported data introduces potential biases, and its cross-sectional design limits insights into long-term behavioral changes. Future research could:

- Employ longitudinal designs to monitor adoption trajectories over time.
- Investigate region-specific barriers and tailor interventions accordingly.
- Explore complementary technologies, such as AI-based systems, to provide a broader understanding of smart farming adoption.

4. Conclusions

This study provides valuable insights into the adoption and sustained utilization of automated mini-greenhouses in the Philippines. Using an integrated theoretical framework combining UTAUT2, DOI, and ANT, the research identifies performance expectancy, social influence, trust, habit, and technological readiness as pivotal factors influencing behavioral intention and continued use. The findings highlight the crucial role of trust and technological readiness in building farmers' confidence and equipping them to integrate this innovation into their daily practices. Furthermore, the study underscores that sustained use is driven by the habitual incorporation of technology into farming routines, reflecting its compatibility and reliability. These findings contribute to advancing smart farming practices, particularly in climate-vulnerable regions. By addressing barriers such as facilitating conditions and leveraging social influence through community networks, policymakers and technology developers can foster wider adoption and long-term sustainability. The study also highlights the limited impact of price value, suggesting that farmers prioritize long-term benefits—such as improved productivity and resilience—over initial costs. However, this study has limitations. Reliance on self-reported data introduces potential biases, and the cross-sectional design restricts insights into the evolution of adoption behavior over time. Future research should adopt longitudinal designs to examine behavioral changes, explore regional variations in adoption, and assess the scalability of automated mini-greenhouses for larger farms or cooperatives. Further investigation into integrating advanced technologies, such as AI and IoT, could also enhance operational efficiency and environmental sustainability. In conclusion, automated mini-greenhouses represent a transformative innovation for the agricultural sector in the Philippines. By addressing key adoption determinants and mitigating barriers, this technology can significantly enhance climate resilience, food security, and sustainability in smallholder farming communities. This research lays the foundation for future studies and practical interventions, contributing to a robust and inclusive framework for smart agricultural development.

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Author Contribution

Conceptualization and Methodology: Eugenia R. Zhuo; Data Collection: Eugenia R. Zhuo, with assistance from trained enumerators; Writing and Revision: Eugenia R. Zhuo; Funding Acquisition: Research Center for Social Sciences and Education, University of Santo Tomas

Competing Interest

No competing interest.

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