JMSS Journal of Multidisciplinary in Social Sciences

Journal of Multidisciplinary in Social Sciences
Journal homepage : https://so03.tci-thaijo.org/index.php/sduhs

Farmers' Application of Smart Agriculture Systems to Climate Change

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Article info

Article history:
Received: 2 May 2024
Revised: 13 December 2024
Accepted: 26 March 2025

Keywords:
Farmers' application of smart, Agriculture systems, Climate change.

Abstract

Climate change has disrupted agricultural practices worldwide, creating serious pressures on food security and environmental sustainability. This study examines how smart agriculture systems can help reduce climate-related impacts on farming, with attention to precision technologies such as IoT-based irrigation, AI-supported crop monitoring, and adaptive greenhouse management. Using a participatory action research approach, data were gathered from in-depth interviews, focus group discussions, and non-participant observations. The study worked with 93 farmers across six districts in Buriram Province, Thailand, and introduced smart farming tools to address three major challenges: water shortages, pest control, and resilience to extreme weather. The results show notable improvements in both efficiency and sustainability. Smart irrigation systems lowered water use by 40%, ensuring more accurate watering based on crop needs. Greenhouse cultivation increased yields by 25%, producing an average of 530 kilograms per unit each year, with stable quality and chemical-free produce. The use of biological pest control reduced pest outbreaks by 60%, decreasing reliance on synthetic pesticides. Economically, production costs fell by 30%, and the average payback period for technology investments was about five years, indicating that these innovations are financially viable. The study also shows that collaboration among researchers, policymakers, and farmers has supported the adoption of these technologies and aligned farming practices with broader environmental goals. Overall, this research highlights the role of smart agriculture in strengthening climate resilience and promoting sustainable development in rural communities. The insights offered can guide stakeholders seeking practical and scalable solutions to current agricultural challenges.

Introduction

Agriculture is both a sufferer and a contributor to the growing climate disaster. Due to the sector's particular vulnerability to the effects of climate change, conventional farming techniques are being challenged by changing precipitation patterns, extreme weather events, and shifting temperatures (Gupta et al., 2021). However, agriculture exacerbates the problem even more by contributing significantly to greenhouse gas (GHG) emissions worldwide. The introduction of application-

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driven smart agricultural systems, which provide creative approaches for adaptation and mitigation to guarantee a sustainable farming future, stands out as a ray of light among this intricate interplay (Riches, 2023).

The Food and Agriculture Organization (FAO) and the Intergovernmental Panel on Climate Change (IPCC) have released new data that highlights the direct consequences of climate change on food security and agricultural output. The average global temperature has risen by approximately 1.2°C over pre-industrial levels, changing precipitation patterns and resulting in more frequent extreme weather events. The productivity of livestock and crop yields has been directly impacted by these changes. According to these studies, wheat yields may decrease by 6%, rice yields by 3.2%, maize yields by 7.4%, and soybean yields by 3.1% for every 1°C increase in global temperature. Water Stress: Droughts and water shortages brought on by climate change have made agriculture very water-constrained for an estimated 1.9 billion people worldwide. As a result of rising temperatures and heat stress, milk production, reproductive rates, and susceptibility to illness have all suffered (de Lima et al., 2023).

Fundamentally, a smart agricultural system makes use of technology to convert agriculture into an exact, data-driven science. These systems offer a new paradigm in agriculture through the integration of sensors, drones, artificial intelligence (AI), and machine learning algorithms with Internet of Things (IoT) devices (Kalbande & Patil, 2023)). They make it possible to monitor and analyze a wide range of agriculturally related variables in real time, including crop health, weather, and soil moisture and nutrient content. This network of information facilitates well-informed decision-making, maximizes resource utilization, and increases agricultural yields while reducing environmental effects (Arthi et al., 2023).

Smart agricultural systems stand at the forefront of mitigating the adverse effects of climate change on agriculture. By enabling precision farming, these technologies ensure the judicious use of water, fertilizers, and pesticides, significantly reducing the ecological footprint of farming activities (Ness, 2023). For example, by precisely adjusting watering schedules and quantities to crops' demands, sensor-based irrigation systems may significantly reduce water use. Similarly, fertilizer application may be optimized by AI-driven insights, lowering runoff and the ensuing eutrophication of water bodies. Furthermore, by encouraging the use of techniques such as cover crops and no-till farming that improve soil carbon absorption, these systems help lower atmospheric CO2 levels (Casey, 2024).

Smart agriculture systems provide strong instruments for climate adaptation beyond mitigation. Farmers may use predictive analytics to foresee and prepare for catastrophic weather events, changing their procedures to protect their crops. Drought-resistant crop types can be chosen to flourish in new climatic circumstances, protecting food supply against the whims of climate change, based on AI assessments of climate trends (Alanne & Sierla, 2022). Furthermore, drone technology and remote sensing can monitor crop health across vast areas, enabling rapid responses to pests or diseases exacerbated by climate shifts. Significant obstacles stand in the way of the broad deployment of smart agricultural systems, notwithstanding their promise. Challenges include the expensive cost of technology and the requirement for farmers to be digitally literate, especially in underdeveloped nations. To further safeguard the interests of farmers, strong legislative frameworks are required in response to concerns about data security and privacy. Governments, IT companies, and the agriculture community must work together to overcome these challenges. Financial incentives and subsidies can reduce the obstacles to farmers adopting technology, while training initiatives can improve farmers' digital literacy. Innovation may be sparked by cooperative research and development, increasing the usability and efficiency of smart agricultural systems.

The advancement of smart farming systems represents a transformative approach to modern agriculture, designed to minimize production costs, optimize yield per unit area, and ensure the consistent quality of agricultural outputs while aligning production standards with consumer requirements. These systems are particularly advantageous for agricultural contexts constrained by limited water resources, restricted land availability, or time-intensive practices. Utilizing open and closed greenhouse configurations, smart farming integrates biologically driven production methodologies with sensor technologies to monitor critical parameters such as temperature, humidity, pH, and soil fertility. Moreover, these systems incorporate automated nutrient management and pest control mechanisms, enhancing overall cultivation efficiency.

With implementation costs ranging from 6,000 to 7,000 baht, these technologies present a viable solution for household-level food production, fostering food security while simultaneously reducing expenditures, boosting household income, and generating employment opportunities. Beyond their economic benefits, these systems play a pivotal role in climate adaptation strategies, as evidenced by this current research initiative. This initiative develops advanced smart farming frameworks and integrates environmentally sustainable practices, emphasizing the use of biological agents throughout all stages of agricultural production. The objectives include cost reduction, productivity enhancement, improved food safety, health benefits, and resilience to climate variability. This initiative has established a collaborative framework involving key stakeholders, including the Buriram Provincial Agricultural Office, the Agricultural Research and Development Bureau Region 4, the Buriram Agricultural Research and Development Centre, and exemplar farmers to amplify its impact. The outcomes of this research are systematically disseminated to diverse audiences and incorporated into annual budgetary plans, ensuring the scalability and sustainability of these tools in facilitating climate adaptation within the agricultural sector.

The research team believes that applying smart agriculture systems in response to climate change is a crucial means of applying participatory action research, for the reasons mentioned above. A collaborative approach that involves all stakeholders, including farmers, researchers, policymakers, and technology developers, in the research process ensures that the development and deployment of smart agriculture technologies are not only technologically sound but also socially inclusive and adaptive to the specific needs of local communities.

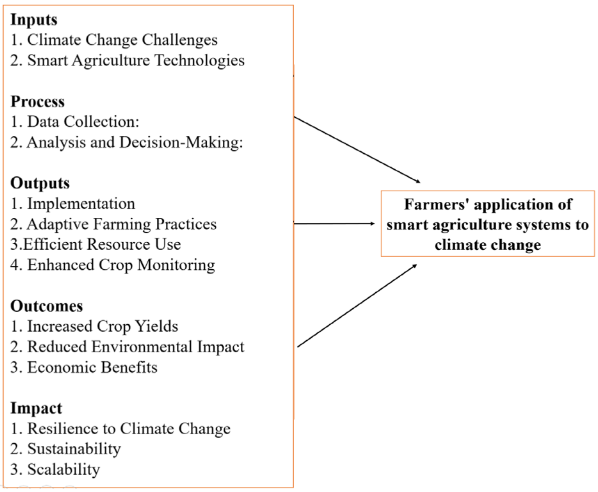

Figure 1 Conceptual Framework

Objective

To implement a smart agriculture system that addresses farmers' challenges related to climate change, aiming to have a transformative impact on agricultural research for improved farming efficiency and sustainability.

Methodology

Using smart agricultural systems is a revolutionary approach to helping farmers address the challenges posed by climate change. In this context, data collection techniques are essential to comprehending implementation hurdles, adaptation strategies, and effectiveness. Primary data collection entails conducting surveys and interviews directly with farmers to gain insights into their perspectives and experiences. Focus groups facilitated group conversations regarding smart agriculture technology, highlighting shared opportunities and challenges. Participant observation in agricultural communities provides deeper insights into real-world applications and environmental interconnections. To complement primary data, secondary data collection methods, such as analyzing agricultural reports and climate change research, were also employed. Together, these methods enabled a comprehensive understanding of how smart agriculture can contribute to climate resilience among farmers, guiding policy and practice towards sustainable agricultural futures.

1. Data Collection

1. In-depth interviews: conducted either face-to-face or virtually with smallholder farmers, agricultural extension workers, and local agricultural technology providers. A semi-structured interview guide was employed to allow for flexibility in discussions, enabling the exploration of new insights regarding individual experiences, perceptions, and the personal impact of smart agriculture in mitigating the effects of climate change. A total of 53 key informants participated in the interviews, including representatives from the District and Provincial Agricultural Offices, the Community Development Office, Sub district Administrative Organizations, and the Buriram Provincial Agricultural Research and Development Center. Additionally, interviews were conducted with urban and rural community members, model farmers, and general farmers across six districts.

2. Focus Group Discussions (FGDs): Organized discussions with groups of farmers, categorized by age, gender, or types of farming production, such as rice and sugarcane. Each group consisted of 6 to 10 participants, with a moderator to guide the conversation around specific topics related to smart agriculture and climate change. This method aimed to gather diverse perspectives and generate debate on shared experiences, benefits, and the challenges of adopting smart technologies in agriculture. A total of 40 participants were divided into four groups: 1. Model farmers (10 participants) 2. Government agency representatives (10 participants) 3. Rural farmers (10 participants) 4. Urban farmers (10 participants). These discussions provided critical insights into the problems and impacts of climate change and the integration of modern agricultural technologies into farming practices.

3. Participant Observation: Time was spent in the communities and on farms to observe day-to-day activities and the practical application of smart agriculture technologies. This approach provided firsthand insight into the practical application of these technologies, including any obstacles faced by farmers in their implementation.

4. Document Analysis: Reviewed existing documents and reports related to agriculture, smart farming initiatives, and climate change policies to provide context and background to enrich the qualitative data collected.

2. Research Steps

The research involved creating a framework that encouraged the active involvement of farmers in applying smart agriculture technologies to adapt to and mitigate the impacts of climate change. A step-by-step approach is outlined below:

1. Define Objectives and Scope: Empower farmers to use smart agriculture systems to improve resilience and adapt to climate change. Define the geographic area, types of crops, and specific climate challenges to be addressed (e.g., drought, flooding).

2. Stakeholder Engagement: Involve farmers, agricultural technology experts, climate scientists, local government, and community organizations. Organize workshops, meetings, and focus groups to gather input, expectations, and concerns from all stakeholders.

3. Needs Assessment and Baseline Data Collection: Conduct surveys and interviews to understand farmers' current practices, challenges, and technology usage. Collect baseline data on current crop yields, farming practices, and climate data to measure project impacts over time.

4. Designing the Participatory Action Research Framework: Collaborate with stakeholders to co-create the research agenda, ensuring it addresses real-world challenges and leverages local knowledge. Identify smart agriculture technologies suitable for the context (e.g., precision farming tools, IoT-based irrigation systems, climate-resilient crop varieties).

5. Training and Capacity Building: Develop training programs for farmers on the use of smart agriculture technologies, tailored to their skill levels and needs.

6. Implementation: Begin with pilot projects in selected areas to test and refine the approach. Establish mechanisms for regular feedback from participants to adjust strategies and technologies as needed.

7. Monitoring, Evaluation, and Learning: Implement a system to regularly collect data on key indicators (e.g., crop yield, water usage, adoption rates of technologies). Assess the project's impact on farmers' resilience to climate change and its sustainability. Use findings to refine the project, scale successful interventions, and share lessons learned.

8. Dissemination and Scaling Up: Organize forums, publish case studies, and leverage social media to share successes and lessons learned. Partner with government agencies, NGOs, and the private sector to expand the project's reach and impact.

3. Target Group

This study focuses on the application of smart agriculture systems to support climate change adaptation among the population of Buriram Province. The key informants for this research comprise individuals with significant roles and expertise in agricultural issues and the challenges posed by climate change, such as farmers' difficulties, plant disease outbreaks, and pest infestations. To obtain a comprehensive and multidimensional perspective, the research team selected a diverse group of target respondents as follows:

1. Representatives from the District/Provincial Agricultural Office (3 individuals): These individuals play a pivotal role in formulating agricultural policies and disseminating agricultural knowledge to farmers. They also have extensive experience in providing guidance on agricultural technologies and climate adaptation strategies.

2. Representatives from the Community Development Office (3 individuals): Their responsibilities include

promoting the economic and social development of local communities. They provide insights into the impacts of climate change on the livelihoods of the local population.

3. Representatives from Sub district Administrative Organizations across six districts (12 individuals): These representatives hold critical responsibilities in managing local resources. They possess a deep understanding of policies and agricultural support programs related to climate change adaptation.

4. Researchers from the Buriram Provincial Agricultural Research and Development Center (5 individuals): These experts specialize in agricultural research and technological development. They provide scientific insights into strategies for mitigating environmental challenges in the agricultural sector.

5. Urban Farmers (20 individuals): These individuals represent the urban population who may experience climate change impacts differently from those in the rural agricultural sector. They provide valuable information on consumer behavior regarding agricultural products and trends in smart agriculture adoption.

6. Rural Community Members (20 individuals): These individuals represent the rural population whose livelihoods may be directly tied to agriculture. They offer perspectives on community-level challenges arising from climate change.

7. Model Farmers (10 individuals): These farmers have actively implemented smart agriculture practices in their fields. They contribute insights into the advantages, limitations, and future development pathways for smart agriculture systems.

8. General Farmers from Five Districts (20 individuals): These individuals represent farmers who have been directly affected by climate change. They provide information on the challenges they face, their needs, and their strategies for adapting to changing environmental conditions.

In total, 93 individuals from governmental agencies, academic institutions, and the local community—each with a connection to smart agriculture in Buriram Province—constitute the study's target respondents. The data collected from these stakeholders will facilitate the development of practical and effective strategies for advancing smart agriculture, thereby mitigating the adverse impacts of climate change.

4. Data Analysis

1. Examination of Climate Change Challenges and Their Impacts: This study investigates the multifaceted challenges arising from climate change, with a particular focus on farmers' comprehension of smart farming technologies and their perceptions regarding the adoption of such innovations. The primary objective is to improve agricultural practices by promoting efficient resource utilization, mitigating risks associated with climate variability, and boosting agricultural productivity. A robust methodological framework, comprising in-depth interviews, focus group discussions, community forums, and document analysis, will support the exploration of these critical issues.

2. Evaluation of the Effectiveness of Smart Farming Technologies: This research further evaluates the efficacy of smart farming technologies in enabling farmers to adapt to the evolving climate landscape. Key areas of focus include advancements in water management practices, the optimization of fertilizer application, and the precision monitoring of crop quality. Moreover, the study examines the economic implications of adopting these technologies, assessing their capacity to reduce costs, enhance return on investment, and increase overall agricultural income. Insights are gathered through a triangulated approach employing in-depth interviews, focus group discussions, community forums, and comprehensive document reviews.

This integrated analysis seeks to provide actionable insights into the role of smart farming systems in fostering sustainable agricultural development in the context of climate change adaptation.

Results

Farmers worldwide are increasingly using smart agricultural systems as a vital adaptation tactic in the face of climate change. These innovative solutions leverage IoT, AI, and big data analytics to empower farmers to make well-informed decisions that maximize production while minimizing environmental impact. Smart agriculture systems integrate sensors and machine learning algorithms to deliver real-time insights into crop health, weather patterns, and soil moisture levels. These technologies enable timely pest management, efficient resource usage, and targeted watering. By enhancing crop yields and resilience to extreme weather events, precision farming not only conserves water but also reduces reliance on chemical inputs. Furthermore, smart agriculture systems support sustainable farming practices and contribute to global efforts to monitor and reduce carbon footprints. Their adoption represents a significant step forward in achieving food security and agricultural sustainability in the face of climate challenges.

1. Application of Smart Agriculture System in Climate Change Adaptation: Farmers are increasingly turning to smart agricultural systems as innovative tools to address the complex issues posed by climate change. These systems provide viable ways to improve agricultural production, resilience, and sustainability in the face of climate uncertainty because they integrate cutting-edge technology and data analytics. With an emphasis on the technology involved, their effects, and the difficulties encountered, this research investigates how farmers are using smart agricultural systems to lessen the effects of climate change and adapt to it (Rahman et al., 2022). To maximize farm management and productivity, smart agriculture makes use of a variety of technologies, including IoT, AI, remote sensing, and precision farming instruments. With the use of these technologies, farmers may make well-informed decisions and implement strategic planning by being able to monitor and react in real-time to a range of environmental and climatic circumstances. Farmers are able to keep an eye on microclimatic factors including soil moisture, temperature, and humidity by using sensors and Internet of Things devices (Soheli et al., 2022). By applying fertilizer and pesticides at the correct times and with precision, this data-driven strategy reduces waste and its negative effects on the environment. It also makes accurate irrigation, planting, and harvesting possible. Precision agriculture allows farmers to map field variability and optimize inputs based on crop and soil requirements by using GPS technology and data analytics. In order to detect early symptoms of illness, insect infestation, or stress in crops and animals, machine learning algorithms analyze data from drones and satellites. This approach greatly increases efficiency while lowering the carbon footprint and promoting sustainable agricultural methods (Mahfuz et al., 2022). Early intervention can prevent significant losses, ensuring food security and the efficient use of resources.

Challenges

Farmers face several challenges related to climate change: 1) insect pests and diseases, 2) root rot during the wet season, and 3) excessive heat.

1. Insect Pests and Diseases: Climate change alters ecosystems, temperatures, and global weather patterns at a rate never seen before. These changes impact insect populations by altering their lifespan, distribution, and behavior, which in turn affects the epidemiology of the diseases they carry and spread (Avesani et al., 2022). As a result of insects being able to thrive in previously too-cold areas, the geographic range of vector-borne illnesses such as Lyme disease, dengue fever, and malaria has expanded. Insect populations can rise as a result of improved breeding conditions brought about by warmer temperatures and altered rainfall patterns. An increased number of insects means an increased risk of disease transmission. Seasonal patterns have changed as a result of climate change; longer, warmer winters allow insects to remain active for extended periods of time. The window of exposure to these diseases may be extended as a result of this expansion, resulting in longer seasons of disease transmission.

Scholars note that “the spread of diseases and pests has increased as a consequence of global warming and other changes.” Insects can multiply more quickly in warm climates with alternating rains, spreading to new regions where plants are less resistant to diseases like leaf blight, rust, and viral infections. Certain insects cause crop damage by destroying agricultural crops. Therefore, to stay up to date with the issues that farmers are facing, the Department of Agricultural Extension must invest in research and the development of biological solutions to address these challenges. While pesticides offer short-term relief, they can exacerbate pest problems over time.

Insect pests and associated diseases pose a serious threat to agriculture, endangering crops, livestock, and global food security. Climate change amplifies these risks, making it imperative to develop adaptive agricultural practices that can withstand shifting climatic conditions.

2. Issues with Root Rot during the Wet Season: Root rot, a damaging plant disease that favors excessively wet soil, has become more prevalent during the rainy season due to climate change. This phenomenon has significant implications for food security, ecosystem health, and agricultural output. This study explores how climate variations, particularly changes in rainfall patterns, intensify soil moisture conditions favorable for root rot pathogens. Potential adaptation and mitigation measures are also explored.

The accumulation of GHGs in the Earth’s atmosphere has altered global weather patterns, resulting in increased rainfall intensity and more frequent flooding (Luck et al., 2011). The increasing intensity and unpredictable nature of rainfall throughout the rainy season is one of the major effects of this shift. These alterations lead to increased precipitation amounts as well as more frequent and severe flooding incidents.

These conditions are especially favorable for the growth and the spread of root rot pathogens, which thrive in soggy soils with inadequate drainage (Wakelin et al., 2018).

Farmers reported that “the issue of root rot typically arises during the rainy season, to the extent that it can occasionally make planting difficult since the plants' roots are bare and rotting, preventing them from growing. When the plants do not reach their full potential, their leaves wither and become yellow, and finally, they die. As a result, there is some loss and no revenue from the sale of vegetables. It is an annual issue. To address the issue, you could choose to construct an open greenhouse, a raised vegetable patch with a roof, and a suitable drainage system. Find biological materials to strengthen the roots of the plants.”

Many fungal and oomycete infections, such as Phytophthora, Fusarium, and Rhizoctonia species, attack plant roots, cause deterioration, and lead to plant death. These pathogens are collectively referred to as root rot. Although these pathogens occur in soil normally, excessive wetness and insufficient oxygen availability to the roots cause them to become more aggressive. Symptoms include yellowing leaves, wilting, and eventual plant death. The connection between root rot infections being worse during the rainy season and climate change is that increased rainfall causes standing water and saturated soils, which foster the growth of root rot pathogens. Climate change affects the temperature and moisture content of the soil, which in turn affects the microbial dynamics and improves the environment for root rot pathogens.

3. Excessive Heat: The survival of species and biodiversity is impacted by habitat modification caused by increased temperatures. It causes temperature zone shifts, coral bleaching, and the melting of polar ice caps, all of which can upset ecosystems' delicate balance and cause the extinction of fragile species. Heatstroke, dehydration, and cardiovascular difficulties are among the health problems exacerbated by rising temperatures. Furthermore, heated air can exacerbate air pollution, worsening respiratory illnesses like bronchitis and asthma and encouraging the spread of infections carried by vectors (Sugawara et al., 2021). Because it decreases soil moisture, exacerbates drought conditions, and disrupts crop growth cycles, hot air is a serious threat to agriculture. Particularly in areas where agriculture plays a major role in sustaining lives, these changes may result in lower agricultural production and jeopardize food security (Vinoth & Elango, 2021).

The head of the Buriram Agricultural Research and Development Centre claims that “the issue of decreased crop yields brought on by extreme heat—often referred to as the "hot food" problem—is one way that climate change is harming agriculture. Plants wilt under extreme heat because it slows down their development and decreases the effectiveness of photosynthesis. For instance, several vegetables, rice, and maize dislike hot temperatures, which lowers their yields. In order to avoid plants from withering and dying, farmers must change the planting season during hot weather, create heat-resistant plant varieties, and ensure a water system is available.”

The effects of hot weather on crop physiology—heat stress brought on by high temperatures—can cause plants to have slower growth rates, poorer yields, and, in extreme situations, may lead to plant mortality. The processes of photosynthesis, respiration, and transpiration are all impacted by heat stress, reducing a plant's capacity to grow and produce food. Due to increased rates of transpiration and evaporation, hot weather frequently exacerbates water scarcity, increasing crop water requirements. This may lead to drought conditions, severely straining crops and lowering yields. Certain temperature ranges are necessary for successful pollination of many crops. The growth of fruits and seeds, essential for crop yields, might be hampered by hot weather. Additionally, warmer temperatures can accelerate the life cycles of several pests and diseases, increasing the susceptibility of crops to infestations and infections. This affects crop health and productivity but also raises the need for pesticides, which has financial and environmental consequences.

Considering the above-mentioned concerns, the research team developed a plan to employ an intelligent farming system to address the problem. Farmers can mitigate against climate change in three ways: 1) Allow farmers to build greenhouses for growing crops and vegetables; 2) Install an irrigation system that evenly distributes water over the plot; and 3) Construct biological material storage containers as an insect deterrent. All three will be completed and connected to the smart agriculture system of the research team to support farmers in overcoming challenges.

Unprecedented difficulties brought about by climate change for agriculture include harsher weather patterns, a shortage of water, and an increase in insect activity. These elements have a significant impact on agricultural production, endangering farmers' livelihoods, and the availability of food. This research team has created an integrated smart agricultural system to address these issues and lessen the negative effects of climate change on farming. This research outlines the components of this novel system, which includes the construction of greenhouses, an effective water distribution system, and the use of biological materials for pest management, all connected through smart technology.

1. Greenhouse Construction for Controlled Agriculture: The first pillar of the team's approach involves encouraging farmers to build greenhouses for crop and vegetable cultivation. Greenhouses offer a controlled environment that can protect plants from extreme weather conditions, including hot weather, heavy rains, and cold snaps. By regulating temperature, humidity, and light within these structures, farmers can significantly enhance crop yields and extend growing seasons. The smart agriculture system integrates sensors and automated controls within the greenhouse to monitor and adjust the environment, ensuring optimal conditions for plant growth.

2. Smart Water Distribution Systems: Water scarcity and uneven distribution are critical issues exacerbated by climate change, necessitating efficient irrigation methods. The researchers' system includes the development of a smart water distribution system that ensures water is delivered evenly and precisely to the areas where crops need it most. Utilizing IoT technology, soil moisture sensors can determine the exact moisture levels across different parts of a farm. Based on this data, the system can automate irrigation schedules, so optimizing water use and reducing waste. This approach not only conserves water but also prevents overwatering or under watering, leading to healthier crops and better yields.

3. Biological Substance Tanks for Pest Management: Pest management is a significant challenge in agriculture, with climate change driving the spread of invasive species and increasing pest populations. To address this, the system proposed incorporates tanks of biological substances that repel insects naturally, reducing the reliance on chemical pesticides. These substances can include bio pesticides derived from natural materials like plants, bacteria, and certain minerals. The smart agriculture system controls the distribution of these biological agents, applying them at optimal times to maximize their effectiveness while minimizing environmental impact.

The core of smart farming innovation lies in integrating these three components into a cohesive smart agriculture system. This system uses advanced technologies such as IoT devices, AI algorithms, and data analytics to monitor and manage agricultural processes in real-time. Farmers can access real-time data on weather conditions, soil health, water levels, and pest activity through a user-friendly interface, enabling informed decision-making and prompt action. By leveraging this technology, farmers can adapt to the changing climate more effectively, ensuring sustainable crop cultivation and food security.

2. Transformative Impact of Agricultural Research on Farming Efficiency and Sustainability: New farming methods have emerged as a result of recent developments in agricultural research, which hold the potential to improve agricultural production's sustainability and efficiency while also easing some of the difficulties farmers now face. The novel techniques developed by this research provide farmers with three important advantages: (1) less time spent watering crops, (2) more consistent and higher crop yields, and (3) cheaper production costs by using locally available waste resources for cultivation. This article explores these results and shows how agriculture might be revolutionized for the better by incorporating these study findings into regular agricultural operations.

2.1 Reduction in Time Spent Watering Vegetables: One of the most immediate benefits observed from the application of recent research findings is the significant reduction in the time farmers need to devote to watering their vegetables. Through the implementation of smart irrigation systems that leverage IoT technology, soil moisture sensors, and automated scheduling, farmers can optimize water usage with precision. These systems can assess the moisture levels of the soil in real time and adjust the watering schedule accordingly, ensuring that crops receive the exact amount of water they need, exactly when they need it. This automation not only conserves water resources but also frees up farmers to focus on other essential tasks, thereby enhancing overall farming efficiency.

The research team has developed an advanced intelligent mist irrigation system leveraging IoT technology to mitigate heat stress within agricultural plots. By employing soil moisture sensors, the system ensures the precise measurement of moisture levels across various farm areas, optimizing irrigation processes. This innovation not only enhances water-use efficiency but also minimizes waste and supports sustainable water conservation practices for farmers. Designed to address the pressing challenges of climate change, the system operates in two distinct modes, online and offline. Both the online and offline modes are described in detail below:

2.1.1 Online System: The intelligent irrigation system incorporates cutting-edge functionalities, enabling farmers to manage watering and fertilization via smartphone applications. With scheduling capabilities, farmers can program irrigation cycles twice daily (morning and evening) and customize fertilization schedules to meet crop-specific needs. Notably, the system supports simultaneous watering and fertilization, providing real-time and automated reports on water and fertilizer usage through the LINE application and a web-based platform. System Requirements: Wi-Fi connectivity, 220V electrical power supply, water pumps, and 12V DC electric valves. The system offers significant operational advantages, reducing watering time from 40–50 minutes to approximately 5–10 minutes. Additionally, it facilitates the seamless integration of bio products into the irrigation process, thus saving time and enhancing agricultural productivity. The system also includes alert notifications via LINE and comprehensive historical data tracking on the web platform, empowering farmers to make informed decisions and improve crop management strategies. This innovation exemplifies a forward-looking approach to agricultural efficiency, aligning with sustainable development goals and addressing future climate resilience needs.

2.1.2 Offline System: To accommodate farmers in areas lacking internet access, the research team developed an offline version of the intelligent irrigation system, tailored to meet their needs and capabilities. This system facilitates twice-daily watering schedules (morning and evening) and customized fertilization schedules, managed via a remote-control interface. Similar to its online counterpart, the offline system significantly reduces watering durations to 5–10 minutes per session while supporting the application of bio products. Although it lacks real-time notifications via LINE, farmers can access historical water usage data through a web-based platform to inform future crop planning strategies. Farmers interact with the system via a dedicated web application, accessible through a direct link. This platform offers both manual and automatic control modes for irrigation and fertilization. In manual mode, users can activate or deactivate water and fertilizer supplies as needed. In automatic mode, the system adheres to pre-set schedules, ensuring reliable and consistent operation.

The research team conducted hands-on training sessions with farmers to ensure proficient use and configuration of the system. For example, a standard configuration includes watering crops at 7:00 AM and 6:00 PM daily for 5 minutes per session. Fertilization is applied every three days for a duration of 1 minute, with subsequent applications calculated based on the most recent fertilization date (e.g., August 26, 2024). The system also monitors water flow rates, enabling detailed analysis of water usage per session, and applies fertilizers at a controlled rate of 8 liters per minute. This offline irrigation solution exemplifies a robust approach to resource-efficient and sustainable agricultural practices. By empowering farmers with technology that is both accessible and practical, the system fosters resilience to climate change challenges while promoting the efficient management of water and fertilizers. Such innovations play a pivotal role in advancing agricultural sustainability and supporting farmers in optimizing productivity under diverse operational constraints.

2.2 Increased and Uniform Crop Production: The research has also led to methods that promote increased and more uniform crop production. By creating controlled environments, such as greenhouses equipped with advanced monitoring and climate control systems, and employing scientifically-backed cultivation techniques, farmers can achieve higher yields while ensuring that their vegetables grow evenly. These technologies and practices help mitigate the adverse effects of unpredictable weather patterns and pests, common challenges exacerbated by climate change. The result is a more reliable and consistent production of vegetables, which can help meet the growing demand for food without compromising quality.

The smart agriculture system manages the uniform distribution of biological agents across the entire farming plot by integrating with the intelligent water system. This integration enhances efficiency while minimizing environmental impacts. The smart agriculture system is interconnected, enabling comprehensive monitoring and management of agricultural operations. Farmers can access real-time alerts and data on weather conditions, soil quality, water levels, and pest activity through an intuitive interface. This access empowers them to make informed decisions and take immediate action. By leveraging this technology, farmers can adapt effectively to changing climate conditions, ensuring sustainable and resilient agricultural practices.

According to data from farmers who utilize the smart farming method, a greenhouse of 4 meters in width and 9.5 meters in length can support approximately 640 salad and cos lettuce plants, 12 plants each with an output of 1 kilogram that can be sold for 100 baht. 53 kg of total output, or 5,300 baht each growing cycle, are produced. Vegetables may be cultivated nine to ten times in a greenhouse in a year, excluding the growing of seedlings and trays, in a cultivation plot for 37 to 40 days. Consequently, the annual harvest amounts to 530 kilograms, or 53,000 baht.

2.3 Reduction in Production Costs through Sustainable Practices: Perhaps the most transformative aspect of this research is its ability to lower production costs by advocating for the use of local leftover materials in cultivation. By utilizing readily available resources such as animal manure, rice straw, and various plant scraps as fertilizers and soil amendments, farmers can significantly reduce their reliance on expensive, commercially produced inputs. This approach not only lowers the cost of production but also promotes a circular economy, where waste products are repurposed to enhance soil fertility and crop health. It represents a move towards more sustainable agricultural practices that benefit not only the farmers but also the environment.

The research team deployed the system across six districts: Lam Plai Mat, Satuek, Chamni, Nang Rong, Ban Kruat, and Non Din Daeng. The selection process prioritized farmers who volunteered and demonstrated a keen interest in adopting smart agricultural systems. These individuals were selected not only for their willingness to innovate but also for their potential to serve as exemplary model farmers. They exhibited the requisite skills, knowledge, and preparedness, both in terms of land and cultivation practices, to act as pivotal knowledge hubs for others aspiring to engage in advanced farming techniques. The smart irrigation system embodies a transformative approach to modern agricultural water management, offering marked improvements in efficiency. Unlike traditional methods, which often involve manual spraying using hoses and result in uneven water distribution and suboptimal yields, this system ensures precise and consistent water delivery. By maintaining optimal soil moisture levels and mitigating temperature fluctuations within greenhouses, the system fosters enhanced crop growth and quality. Moreover, it significantly reduces water loss, setting a new benchmark for sustainable agricultural practices.

Table 1 provides a comparative analysis of traditional farming methods versus smart agriculture practices within greenhouse systems, highlighting the measurable advantages of this technological intervention.

Table 1 A Comparative Analysis of Traditional Farming Methods versus Smart Agriculture Practices

Comparison Aspects	Traditional Agriculture	Smart Agriculture in Greenhouse Systems
Initial Cost	Initial Cost: Low (5,000 - 20,000 baht per rai)	Initial Cost: High (50,000 - 100,000 baht per rai)
Labor Cost	Labor Cost: High, averaging 30-50% per production cycle	Labor Cost: Reduced to only 5-15% per production cycle due to automation
Water Usage	Water Usage: High, averaging 1,500 - 2,500 cubic meters per rai/year	Water Usage: Reduced, averaging 800 - 1,200 cubic meters per rai/year
Fertilizer and Chemical Usage	Fertilizer and Chemical Usage: Average cost is 10-20% per production cycle	Fertilizer and Chemical Usage: Reduced, averaging 5-10% per production cycle due to precise fertilizer application systems, with increased use of organic fertilizers for cultivation
Losses from Pests	Losses from Pests: Average cost is 10-30% of total yield	Losses from Pests: Reduced to approximately 5% of yield due to decreased chemical use, improved agricultural ecosystems, and increased use of bio-agents from the Department of Agriculture to minimize environmental impact
Yield per Rai/Year (or Yield per Unit Area/Year)	Yield per Rai: 1,000 - 2,000 kg	Yield per Rai: 4,000 - 5,000 kg
Quality of Produce	Quality of Produce: Inconsistent	Quality of Produce: High and consistent, free from chemical residues, with improved agricultural ecosystems
Risk from Weather Conditions	Weather Risk: High, including risks from drought, flooding, and temperature fluctuations	Weather Risk: Minimized due to controlled temperature, humidity, and lighting systems
Energy Usage	Energy Usage: Low, as electricity usage is minimal	Energy Usage: Farmers adopt alternative energy, particularly solar panels, reducing energy costs. Only electrical devices for greenhouse system control incur costs.
Production Cost per Unit	Production Cost per Unit: Average of 10-20 baht per kg	Production Cost per Unit: Average of 5-8 baht per kg
Payback Period	Payback Period: Short (1-3 years)	Payback Period: Long (3-7 years)
Long-term Cost-effectiveness	Long-term Cost-effectiveness: Relatively low (depending on environmental conditions and labor availability)	Long-term Cost-effectiveness: High (stable and effective in reducing losses)

Source: Data derived from the analysis of farmer groups engaged in the project.

Figure 2 Farms that Employ Intelligent Agricultural Technologies

Recent agricultural research findings make a strong case for the adoption of clever, sustainable farming techniques. Farmers can reap a triple dividend by leveraging technology and adopting sustainable practices. They can save time on mundane chores such as watering, boost crop yields, guarantee growth consistency, and lower production costs by using locally available, leftover materials. In addition to meeting farmers' immediate needs, this all-encompassing strategy advances the more general objectives of environmental sustainability and food security. The potential for revolutionizing farming and food production is enormous, signaling a future where agriculture is efficient and sustainable when these study discoveries are incorporated into agricultural practices globally.

Discussion

The application of smart agriculture systems by farmers as a response to climate change has demonstrated significant positive outcomes, reshaping agricultural practices towards resilience and sustainability. These systems integrate advanced technologies such as IoT, AI, and remote sensing to optimize resource use, improve crop yields, and reduce environmental impacts.

1. Enhanced Crop Resilience and Yield: One of the most notable results is the enhanced resilience of crops to climate variability. Smart systems enable precise monitoring and control of environmental conditions, allowing farmers to adapt to changing weather patterns more effectively. This adaptability has led to more stable and increased yields despite the challenges posed by climate change, such as unpredictable rainfall and extreme temperatures (Karri & Nalluri, 2024). The adaptability offered by these smart systems is crucial in countering the adverse effects of climate change. Unpredictable rainfall and extreme temperatures can devastate crops, leading to food scarcity and economic losses. However, with smart agriculture technologies, farmers can swiftly respond to such variability (Arthi et al., 2023). Automated irrigation systems ensure crops receive the right amount of water at the right time, reducing the risk of drought stress or waterlogging. Similarly, climate-controlled greenhouses and shade systems can protect plants from extreme heat, cold snaps, and damaging winds. The result of integrating smart agriculture systems is a marked increase in crop resilience. Crops are better equipped to withstand the stresses of climate change, from prolonged droughts to sudden frosts. This resilience translates to more stable yields year after year, providing a measure of security for farmers facing the uncertainty of a changing climate.

2. Water Use Efficiency: Water scarcity, exacerbated by climate change, poses a significant threat to agriculture. The implementation of smart irrigation systems has proven to be a game-changer, optimizing water use through precise scheduling and volume control based on real-time soil moisture data. This not only conserves water resources but also ensures that crops receive the right amount of water at the right time, enhancing water use efficiency and reducing wastage (Anoop & Bala, 2023). Smart irrigation technology harnesses the power of real-time soil moisture data,

weather predictions, and advanced algorithms to optimize irrigation schedules and water volumes. Unlike traditional irrigation methods, which often operate on predetermined schedules regardless of actual crop need or soil moisture levels, smart systems adjust watering based on the precise requirements of the crop at any given time. This responsiveness to real-time conditions not only conserves water but also prevents the common issues of overwatering or under watering (Tace et al., 2022).

Moreover, the benefits of smart irrigation extend beyond water savings. By providing crops with the optimal water levels for their growth, these systems contribute to healthier, more resilient plants. This can lead to improved crop yields and quality, which are critical in the face of increasing global food demand. Furthermore, efficient water use helps maintain soil integrity, preventing erosion, nutrient leaching, and salinization, common consequences of excessive irrigation. The environmental implications of adopting smart irrigation systems are profound. In regions where water scarcity is a pressing issue, the ability to do more with less water can be a game-changer. Additionally, by reducing the volume of water needed for agriculture, more water can be preserved for other uses, such as drinking and sanitation, further underlining the holistic benefits of smart irrigation in managing the world's limited water resources.

3. Reduced Environmental Footprint: Smart agriculture systems contribute to a reduction in the environmental footprint of farming operations. By optimizing the application of inputs such as fertilizers and pesticides, these systems minimize runoff and leaching, thereby reducing pollution and preserving soil health. Additionally, data-driven farming practices can lead to a decrease in GHG emissions by enhancing resource use efficiency and promoting sustainable land management practices (Palniladevi et al., 2023). In the quest for sustainable agriculture, reducing the environmental footprint of farming operations is paramount. Smart agriculture systems emerge as a beacon of innovation in this regard, offering data-driven solutions that significantly mitigate the ecological impact of traditional farming practices. By integrating advanced technologies to optimize the use of inputs such as fertilizers and pesticides, smart agriculture not only enhances productivity but also champions environmental stewardship (Rao et al., 2023).

The application of fertilizers and pesticides in conventional agriculture often exceeds crop requirements, leading to runoff and leaching into surrounding ecosystems. This excess can contaminate water sources, harm aquatic life, and degrade soil quality. Smart agriculture systems address this issue head-on by employing precision farming techniques. These techniques leverage IoT sensors, satellite imagery, and drone technology to assess crop health and soil conditions in real-time. Armed with this data, farmers can apply the exact amount of inputs needed, precisely where and when they are needed, minimizing the risk of runoff and leaching (Mehta et al., 2023).

Moreover, smart agriculture contributes to the reduction of GHG emissions, a critical aspect of its environmental benefits. Traditional farming practices, particularly those involving intensive tillage and over-application of synthetic fertilizers, are significant sources of GHGs. Smart systems counteract this by facilitating more efficient resource use. For instance, precision irrigation minimizes water wastage, while targeted fertilizer application prevents the overuse of nitrogen-based products, which can emit nitrous oxide, a potent GHG. By optimizing input usage, smart agriculture not only conserves resources but also curtails emissions associated with their production, distribution, and application.

Sustainable land management is another area where smart agriculture makes a substantial impact. Through data analytics and AI, farmers can gain insights into crop rotation strategies, cover cropping, and conservation tillage practices that enhance soil health and biodiversity. These practices not only sequester carbon, reducing the amount of CO2 in the atmosphere, but also improve the resilience of the land to climate change. By promoting healthier ecosystems, smart agriculture helps ensure the long-term viability of farming lands.

4. Economic Benefits: Farmers adopting smart agriculture technologies have reported economic benefits, including reduced operational costs and increased profitability. The efficiency gains from optimized input use and the increase in yields translate into higher income margins. Furthermore, the ability to predict and mitigate the effects of climate change reduces the risk of crop failure, providing a more stable economic outlook for farmers (Simo et al., 2022).

One of the most immediate benefits of smart agriculture is the significant reduction in operational costs. Traditional farming practices often involve a one-size-fits-all approach to the application of water, fertilizers, and pesticides, leading to wastage and inefficiencies. Smart agriculture technologies, on the other hand, utilize precision farming techniques enabled by IoT devices, sensors, and advanced analytics. These systems allow for the meticulous monitoring and management of farm resources, ensuring that inputs are applied optimally. By targeting the exact needs of crops at precise times and locations, farmers can minimize the overuse of resources, cutting down on expenses associated with water, energy, and chemical inputs (Acharya et al., 2022).

Additionally, the predictive capabilities of smart agriculture technologies offer a crucial advantage in mitigating the risks associated with climate change. By analyzing weather data and climate patterns, these systems enable farmers to anticipate adverse conditions, such as droughts, floods, or pest infestations, and take preemptive measures to protect their crops. This proactive approach reduces the likelihood of crop failure, safeguarding farmers' investments and providing a more stable economic outlook. The ability to predict and adapt to environmental challenges not only secures current operations but also ensures long-term sustainability and resilience in the face of climate variability.

Despite these positive outcomes, challenges remain, including the high initial costs of technology adoption, the need for technical skills, and the digital divide between regions. Addressing these challenges requires concerted efforts from governments, industry stakeholders, and the agricultural community to provide support, training, and access to affordable technology solutions.

Suggestions

The use of cutting-edge technologies in agricultural crop production is known as "smart agriculture systems," and it increases productivity, sustainability, and efficiency. Here are some recommendations for successfully implementing these systems:

1. Accurate Agriculture: To monitor and manage land resources more effectively, utilize IoT devices and GPS technologies. The exact use of herbicides, fertilizers, and water in precision farming may drastically save on expenses and have a positive environmental impact.

2. Water and Soil Sensors: Adopt the use of nutrient and soil moisture sensors to collect real-time information on the health of the soil. With the use of these sensors, irrigation plans and fertilizer applications may be made more efficient, giving crops the nourishment they require for optimum development.

3. Systems for Automatic Irrigation: Invest in intelligent irrigation systems that can automatically modify watering schedules in response to plant water demand, soil moisture content, and weather forecasts. This system can prevent crops from being over- or under-watered and result in considerable water savings.

4. Crop Monitoring and Management Software: To track crop health and forecast yields, adopt cutting-edge software systems that combine data from several sources (sensors, drones, and satellite photos). These platforms have the capacity to offer practical insights, allowing farmers to take proactive measures and make informed decisions based on data.

5. Sources of Renewable Energy: Utilize sustainable energy sources to run smart farm systems, such as solar or wind power. In the long run, this can reduce costs and lessens the carbon imprint of farming activities.

6. Education and Training: Ensure that agricultural laborers and farmers receive instruction in the application of smart agriculture technology. This entails being able to use new machinery, analyze data, and use knowledge to enhance crop-cultivation techniques.

The following policy recommendations outline a strategic framework to integrate smart agriculture solutions for mitigating climate change impacts. These recommendations encompass four key areas:

1. Developing Comprehensive Data Systems for Smart Agriculture: Researchers and academics should spearhead the development of centralized, integrated databases that connect critical agricultural data, such as weather patterns, soil quality, water availability, and crop conditions. These databases would enable farmers to make informed decisions, supported by predictive analytics leveraging IoT technology and big data. The initiative should also promote rural farmers' access to these technologies through public-private partnerships, facilitating precise resource management and climate forecasting.

2. Establishing Regional Smart Agriculture Knowledge Networks: To enhance knowledge dissemination, regional Smart Agriculture Learning Centers should be established to provide farmers with localized training on adopting suitable technologies. These centers would emphasize hands-on capacity-building, focusing on resource management strategies to minimize GHG emissions. Furthermore, academic institutions, researchers, and local communities should collaborate in co-developing smart agriculture technologies tailored to specific

regional needs, fostering inclusivity and innovation.

3. Implementing Financial Incentives and Support Mechanisms: The government should create financial support frameworks to assist farmers transitioning to smart agriculture practices. This includes low-interest loans, start-up grants, and tax incentives for purchasing environmentally friendly agricultural technologies. Additionally, certification programs for eco-friendly agricultural products should be promoted, enabling farmers to gain market advantages and increase the value of their produce.

4. Establishing Sustainable Policies and Legal Frameworks: Policies and regulations should be revised to align with the principles of smart agriculture. This involves updating legislation related to water resource management and land use to facilitate sustainable agricultural practices. Initiatives such as the development of smart water reservoirs and renewable energy-powered irrigation systems should be prioritized. Moreover, fostering international collaborations would enable the exchange of advanced technologies and best practices, strengthening the resilience of Thailand's agricultural sector against climate change challenges.

By implementing these recommendations, Thailand can enhance the adaptability and sustainability of its agricultural sector, ensuring a tangible reduction in climate change impacts while advancing long-term resilience and productivity.

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