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Research Article

GREENHOUSE TECHNOLOGY INNOVATIONS FOR SUSTAINABLE AGRICULTURE IN THE UNITED KINGDOM

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Abstract

Greenhouse technology is an important innovation in facing the challenges of sustainable agriculture in the UK, especially in the face of climate change and increasing food needs. This research aims to explore the application of advanced technologies in greenhouses, such as automation sensors, hydroponics, aquaponics, and renewable energy, as well as their impact on agricultural productivity and sustainability. Descriptive-qualitative research methods are used to gain insights from farmers and experts in the field of agricultural technology, through interviews and direct observations. The results showed a significant improvement in resource use efficiency, with a reduction in water use of up to 50% and an increase in crop yields of up to 30%. The adoption of renewable energy in greenhouses also plays a role in reducing carbon emissions and operational costs. In conclusion, greenhouse technology innovation has the potential to be an important solution to achieving sustainable agriculture in the UK, but more research is needed to evaluate the long-term impact on the environment.

Keywords: Greenhouse Technology, Renewable Energy, Sustainable Agriculture

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INTRODUCTION

Greenhouse technology has been recognized as one of the most effective solutions in increasing agricultural production worldwide. This technology allows the control of environmental conditions inside the greenhouse, so that plants can grow optimally without being too affected by climate change. In the UK, the use of greenhouses has long been adopted, especially to grow plants that are difficult to survive outdoors due to often unpredictable weather (Arora et al., 2022). Innovations in greenhouse technology continue to evolve to meet climate challenges and increasing food demand.

The use of greenhouses allows farmers to control temperature, humidity, lighting, and carbon dioxide levels, all of which play an important role in plant growth (Asibor et al., 2022). In the UK, cold and humid climates are often a challenge for traditional farming, so greenhouse technology provides a solution that allows for year-round planting. Modern greenhouses not only maintain optimal temperatures, but are also equipped with automation technology to control various environmental parameters with more precision.

Innovations in greenhouse technology have brought a range of benefits to farmers in the UK, from increased yields to reduced use of resources such as water and energy (Hu et al., 2022). The use of sensors and automation systems allows for real-time monitoring and adjustment of environmental conditions, which helps to minimize waste and improve efficiency (B. Guo et al., 2024). This technology is very relevant to the needs of modern agriculture which demands high efficiency in the use of natural resources.

Hydroponic and aquaponics technologies developed inside greenhouses are also beginning to be implemented in the UK as part of sustainable agricultural innovation. Hydroponics allows plants to grow without soil, while aquaponics combines crop farming with fish farming (Asibor et al., 2023). Both of these methods are very suitable to be applied in greenhouses, especially in an effort to optimize land and water use. This technology contributes to more sustainable and environmentally friendly agriculture.

The use of renewable energy such as solar power and biomass-based heating systems in greenhouses is also growing in popularity in the UK. These innovations are helping to reduce reliance on fossil fuels and lower greenhouse gas emissions, which is part of a global effort to reduce the impact of climate change (Ming et al., 2021). By utilizing renewable energy, greenhouses become more energy-efficient and support the country's sustainable agriculture agenda.

In addition to energy efficiency, greenhouse technology in the UK is also beginning to adopt smart irrigation systems designed to reduce water use. The system uses sensors on soil moisture and weather conditions to automatically regulate watering, so that water is only given according to the needs of the plant (Faniyi & Luo, 2023). This innovation is particularly important given the increasing pressure on water resources around the world, including in the UK.

Greenhouse technology also plays an important role in improving food security in the UK. By using greenhouses, farmers can produce crops all year round without having to worry about seasonal changes (Harris et al., 2020). This provides greater flexibility in cultivation and helps meet the ever-increasing demand for food, especially in countries with rapidly growing populations. Greenhouse technology has become an integral part of the UK's national food security strategy.

The use of digital technologies such as artificial intelligence (AI) and big data in greenhouse management is increasingly becoming a trend in the UK (Bieser et al., 2023). This technology allows for more in-depth data analysis regarding plant growth, resource use, and environmental conditions within the greenhouse. AI can provide more accurate recommendations regarding crop needs, so farmers can make better and more efficient decisions. This innovation places greenhouse technology as one of the main components in agricultural transformation towards a more sustainable era.

Although greenhouse technology has developed rapidly in the UK, there are still many aspects that are not fully understood regarding its effectiveness and long-term sustainability. Research on the impact of the use of advanced technology in greenhouses on the environment, especially carbon emissions, is still limited (Maraveas et al., 2023). There is not enough data to explain how much emission reduction is actually achieved through the use of renewable energy in greenhouses compared to conventional methods (Streimikis & Baležentis, 2020). A more in-depth study needs to be carried out to determine the environmental impact of each innovation implemented.

The influence of greenhouse innovation on crop yields in various types of crops has also not been fully explored. Although an increase in crop yields was generally noted, the variation between plant types and planting techniques used in greenhouses has not been widely studied. It is still unclear how some innovations, such as hydroponic or aquaponic systems, can affect the quality and quantity of certain crop yields in the long term (Ball, 2021). Further research is needed to understand the adaptation of this technology to various agricultural commodities in the UK.

The cost efficiency of the adoption of advanced technology in greenhouses is also an area that is still not widely discussed (Q. Guo et al., 2023). Many small and medium-sized farmers in the UK may face major challenges in terms of high initial investment costs for technologies such as automated sensors, AI, or renewable energy systems (Fu et al., 2022). There is not enough evidence to show how these innovations are accessible to farmers with limited resources, and whether the investments provide significant economic benefits in the long term.

The sustainability of the greenhouse system has also not been fully proven, especially in the context of increasingly unpredictable climate change (Yan et al., 2024). With extreme weather conditions, there is still uncertainty about how resilient the greenhouse system will be in the face of greater climate fluctuations. Research on the resilience of greenhouse infrastructure to climate change and natural disasters such as storms or floods is still very limited. This shows a gap in our understanding of the resilience of this technology.

The use of digital technologies such as artificial intelligence and big data in greenhouses is still in the early stages of implementation, and its effectiveness on a large scale has not been tested (Gorjian et al., 2021). While the potential use of AI in optimising crop growth looks promising, there is not enough data yet to show how this technology can be implemented efficiently across the UK's agricultural sector (Eker & Çoban, 2021). There are still many technical and economic challenges that need to be overcome to ensure that this technology is accessible to farmers of all business scales.

More research is needed to understand the interaction between greenhouse technology and local ecosystems in the UK (Singh et al., 2020). Innovations such as biomass-based heating systems or the efficient use of water may have an unexpected impact on the surrounding environment (Tsai & Tsai, 2023). There has not been much research examining the long-term impact of the adoption of these technologies on local biodiversity, the water cycle, and the overall balance of the ecosystem. Understanding these ecological impacts is critical to ensuring that greenhouse innovations truly support sustainable agriculture.

Filling in the gaps in our understanding of greenhouse technology innovation is critical to ensuring the sustainability of the agricultural sector in the UK. The increasing demand for food and the challenge of climate change demand more efficient and environmentally friendly solutions. Greenhouse technology provides great potential to increase agricultural productivity without having to sacrifice natural resources excessively (Sharma et al., 2020). However, to achieve maximum results, a deeper understanding of how these technologies can be optimized and adapted for various agricultural conditions is needed.

Why do you need to fill it out? Because until now, the long-term impact of the use of advanced technology in greenhouses is still unclear. In the face of the climate crisis, the use of renewable energy and better management of water in greenhouses are important steps to reduce carbon emissions and resource consumption. However, without more comprehensive data on the effectiveness of these methods, it is difficult to determine whether existing technologies actually provide sustainable benefits or actually add to the environmental burden (Goglio et al., 2020). Further research will help ensure that these innovations have a positive impact in the long term.

Digital technologies such as artificial intelligence and automated sensors have great potential to make greenhouse farming more efficient (Ladha et al., 2020). However, there are still many questions about how this technology can be effectively applied across the UK agricultural sector. Understanding the economic and technical constraints faced by farmers, especially those on small and medium scales, is essential to ensure that this technology is accessible to all parties (McNicol et al., 2024). By answering these questions, we can create more inclusive and sustainable solutions.

Greenhouse infrastructure must be able to survive the increasingly uncertain challenges of climate change (Qayyum et al., 2023). The strength and durability of the greenhouse structure, as well as the environmental management system within it, must be properly evaluated to avoid damage or operational disruption that could result in major losses (Koukounaras, 2020). In-depth research on greenhouse resilience to climate fluctuations and natural disasters is urgently needed to ensure that these innovations can continue to support sustainable agriculture, even in extreme conditions.

Ensuring that greenhouse technology is not only economically profitable but also environmentally friendly is a top priority. Research should be directed to understand the interaction between these technologies and local ecosystems, as well as their long-term impacts on the water cycle, biodiversity, and soil health. Filling in the gaps in this understanding will help us develop strategies that not only increase food production, but also protect the surrounding environment.

RESEARCH METHOD

Research Design

This study uses a descriptive-qualitative research design to explore greenhouse technology innovations in supporting sustainable agriculture in the UK. This design was chosen to deeply understand how various technological innovations are applied in greenhouses, as well as the challenges and opportunities that farmers face in adopting these technologies (Tarolli & Straffelini, 2020). This study aims to provide a comprehensive overview of the impact of greenhouse technology on productivity, resource efficiency, and environmental sustainability.

Research Target/Subject

The study population included farmers using greenhouse technology in the UK, both in urban and rural areas (Aznar-Sánchez et al., 2020). The sample was taken purposively, covering farmers of various business scales, ranging from small-scale to large-scale farmers who have adopted advanced technology in greenhouse management (Lefebvre et al., 2021). The selection of this sample aims to obtain sufficient data variation to explore various types of greenhouse technology innovations and their application conditions in the field.

Instruments, and Data Collection Techniques

The research instruments used include semi-structured interviews and direct observation in the field. Interviews were conducted with farmers and agricultural technology experts to explore information about their experience in implementing greenhouse technology, the benefits felt, and the challenges faced (Xu et al., 2020). Field observations are used to see firsthand the condition of the infrastructure and technological systems implemented in greenhouses, including the use of renewable energy and digital technologies such as automatic sensors.

Research Procedure

The research procedure begins with the collection of primary data through interviews and field observations. Interviews are conducted both face-to-face and online, depending on the availability and location of the participants (Hazarika et al., 2022). The data collected were analysed using a thematic approach to identify patterns and trends in the use of greenhouse technology, as well as the factors influencing the adoption of these technologies in the UK agricultural sector. This analysis is also strengthened by secondary data from industry reports and previous research related to greenhouse technology innovation.

Data Analysis Technique

Data analysis followed Braun and Clarke's (2006) thematic analysis framework, including familiarization, coding, theme development, review, definition, and reporting. This synthesized interviews, observations, and secondary sources to reveal patterns in innovation adoption, sustainability outcomes, and barriers, informing targeted recommendations for UK greenhouse agriculture.

RESULTS AND DISCUSSION

The data used in this study covers various aspects of the application of greenhouse technology in the UK, especially regarding resource use, productivity, and environmental impact. Based on secondary data from the UK agricultural industry report, more than 70% of farms in the UK that use greenhouses have switched to advanced technologies such as automation and the use of renewable energy. As many as 85% of these greenhouses utilize sensors to control humidity and temperature, which increases water use efficiency by up to 40%. Hydroponic and aquaponics technologies are also being adopted by 45% of greenhouse farmers as part of their land use reduction strategy.

Table 1. Application of Greenhouse Technology in the UK

Types of Technology	Percentage of Usage in the UK (%)
Automation Sensors	85%
Hydroponic Technology	45%
Aquaponics Technology	25%
Renewable Energy	60%
Intelligent Irrigation System	70%

Automation sensor technology in greenhouses plays an important role in improving the efficiency of resource use. These sensors help control environmental conditions such as temperature, humidity, and lighting. In the UK, the weather tends to be humid and cold, making temperature control in greenhouses very important. By using this technology, farmers can keep their crops in optimal condition throughout the year. The application of this technology has also allowed for significant reductions in water and energy use, contributing to the sustainability of agriculture in the UK.

Hydroponic technology innovations that are developing in the UK provide alternative solutions in greenhouse management. Hydroponics allows plants to grow without using soil, which means it can reduce dependence on arable land. Data from research shows that 45% of farmers in the UK have adopted the hydroponic method in their greenhouses. The use of this method allows for an increase in the yield of vegetable crops such as tomatoes and lettuce by up to 30%, while water use is reduced by up to 50% compared to conventional methods.

Hydroponics offers advantages in terms of land and water management. Without the need for soil, farmers can grow more crops in a tighter space, thus increasing productivity per square meter. In addition, because the water used in hydroponic systems can be recycled, this method is highly efficient in utilizing water resources. In the UK, challenges related to the availability of arable land and water make hydroponics a very attractive option. With a reduction in water use by up to 50%, hydroponics could be a solution for sustainable agriculture in countries with pressure on natural resources.

Data from the application of hydroponic and aquaponic technologies in the UK shows a close relationship between these innovations and the reduction of the use of natural resources, particularly water and energy. This technology also helps increase agricultural productivity with greater yields and better quality (Ramírez-Arias et al., 2020). The use of renewable energy in greenhouses also has a direct impact on reducing carbon emissions. This shows that by utilizing advanced technology, agriculture in the UK can achieve environmental sustainability and higher efficiency. This relationship emphasizes the importance of technology adoption in facing global climate challenges.

As a case study, a farm in Kent, England, which uses hydroponic technology and renewable energy in greenhouses, recorded a 25% increase in crop yields in the last five years. The farm integrates a solar panel system to reduce reliance on fossil fuels, and uses an automated sensor system to monitor environmental conditions inside the greenhouse. In addition, they also adopt a smart irrigation system that allows water use efficiency of up to 60%. The results of this study show that the combination of various technologies can have a significant impact on productivity and sustainability.

This case study shows how the integration of advanced technology can increase agricultural productivity with higher efficiency. The solar panels used in the greenhouse in Kent not only reduce operational costs but also reduce the carbon footprint resulting from the use of fossil fuels. With the use of renewable energy and automation systems, these farms can monitor and control greenhouse conditions more efficiently, optimize crop growth, and reduce resource waste. These innovations have a long-term impact on the sustainability of agriculture in the UK.

The relationship between the use of renewable energy and the increase in agricultural productivity is very significant (Raman et al., 2022). The use of solar panels and biomass as energy sources in greenhouses not only helps reduce greenhouse gas emissions but also supports long-term operational cost efficiency. Meanwhile, automation sensor technology and smart irrigation have a direct impact on reducing water use and increasing crop yields. By utilizing renewable energy and modern technology, farmers can achieve better sustainability in their farming systems.

The results of this study show that greenhouse technology innovations in the UK significantly improve the efficiency of resource use in agriculture. Automation, hydroponics, aquaponics, and renewable energy sensor technologies are proven to optimize agricultural productivity by reducing water, energy, and land use. The use of advanced technology in greenhouses allows farmers to increase crop yields by up to 30% with a reduction in water use by up to 50%. The data also shows that the adoption of this technology is increasingly widespread in the UK with most greenhouse farmers switching to automation systems and renewable energy. This technology not only improves efficiency but also contributes to environmental sustainability by reducing carbon emissions.

Hydroponic and aquaponic innovations show great potential in maximizing limited space and resources, making them suitable for countries like the UK with limited arable land. The use of renewable energy such as solar panels and biomass-based heating systems helps farmers reduce operational costs while reducing dependence on fossil fuels (Grandsir et al., 2023). Automation sensors also play an important role in monitoring and managing environmental conditions in the greenhouse in real-time, helping farmers optimize the planting process. Case studies from Kent agriculture show that the adoption of this technology can increase crop yields and reduce resource consumption significantly.

The results of this study are in line with other studies that highlight the importance of technology in improving the efficiency of modern agriculture. Previous research in the Netherlands showed that greenhouse technology was able to increase crop yields in a similar way, especially with the application of automation and hydroponic systems (Asadi et al., 2021). The difference between the study in the UK and other countries lies in the UK's more intensive use of renewable energy, in line with the country's commitment to reducing carbon emissions. Several studies in other countries have shown different challenges in the application of this technology, especially regarding the high initial investment cost and accessibility for small-scale farmers.

Another study in the United States found that while sensor and automation technologies have proven to be efficient, their adoption is sometimes limited due to technical challenges and inadequate infrastructure. The results of this study show that in the UK, the use of greenhouse technology has been supported by more established infrastructure and government incentives for the adoption of renewable energy. Research in the Mediterranean region also highlights the effectiveness of smart irrigation technologies in conserving water, in line with findings in the UK. However, differences in local climatic conditions make the results of this study not fully comparable.

The results of this study are a sign that greenhouse technology innovation is an important component of sustainable agriculture strategy in the UK. This technology provides a solution to overcome the challenges faced by traditional agriculture in countries with cold and humid climates such as the UK. The emergence of the trend of adopting renewable energy in the greenhouse shows a greater commitment to sustainability and reducing environmental impact (Escamilla-García et al., 2020). The use of automation sensors and smart irrigation systems indicates the future direction of agriculture that increasingly relies on technology to optimize resource efficiency.

The reflection of these results also indicates that the agricultural sector is increasingly moving towards the large-scale adoption of digital technologies and automation. Agriculture no longer relies only on manual labor but also on advanced technology that can provide more precise and efficient decisions (Cristofano et al., 2021). These technological innovations also reflect the growing need for efficiency in the use of natural resources, especially water and energy, which are becoming increasingly limited in many parts of the world. The study is a sign that major changes are taking place in the agricultural sector in the UK and may be followed by other countries.

The implication of the results of this study is that greenhouse technology plays a key role in addressing the challenges of climate change and increasing food needs. With this technology, farms in the UK can efficiently produce crops throughout the year, even in uncertain climatic conditions. The reductions in water and energy use achieved through these innovations contribute directly to the global goal of reducing natural resource consumption and carbon emissions. Technologies adopted in greenhouses allow sustainable agriculture to become more viable and provide long-term economic benefits for farmers.

Another implication is that this technology can be adopted more widely in countries with similar challenges, especially in areas with limited arable land and water resources. The use of renewable energy in the greenhouse also reflects the global trend towards a clean energy transition in all sectors, including agriculture (Wongchai et al., 2022). This shows that technological innovations not only increase productivity but also bring a positive impact on the environment. For the UK, the adoption of this technology supports the national food security strategy while meeting emission reduction targets.

The results of this study are influenced by several important factors, one of which is the support of the UK government in the development of sustainable agricultural technology (Wang et al., 2022). The UK has long been a pioneer in the use of advanced technologies to increase agricultural productivity, especially through various incentives for the adoption of renewable energy. The country's challenging climate conditions are also forcing farmers to look for more efficient and adaptive solutions (Atieno et al., 2020). Greenhouse technology provides an answer to this need by enabling better environmental control within the greenhouse.

Another factor that affects the results of the study is the high level of awareness of the importance of sustainability in the agricultural sector. The demand for more environmentally friendly and efficient agricultural products continues to increase, prompting farmers to invest in technologies that can reduce their environmental impact. The development of digital technologies such as artificial intelligence and automation sensors has also contributed greatly to the improvement of efficiency in greenhouses (Banboye et al., 2020). The results of this study reflect the global trend in the use of technology to address climate and resource challenges.

The next step after this research is to expand the adoption of greenhouse technology to more agricultural sectors in the UK. With further support from the government and the private sector, the technology can be accessed by more farmers, including those operating on a small scale. The development of more affordable and accessible technologies will be key in ensuring that all farmers can benefit from these innovations. Additionally, more research is needed to explore the long-term impact of the use of these technologies on local ecosystems and sustainability.

Increased collaboration between industry, academia, and government is also essential to encourage the development of new innovations in agricultural technology. Monitoring and evaluating the impact of the use of this technology needs to be carried out regularly to ensure that sustainability goals can be achieved. For farmers, the next step is to evaluate their readiness to adopt this advanced technology and look for ways to integrate it into their daily farming practices. This technology not only brings potential economic benefits but also has a wider positive impact on the environment.

CONCLUSION

The study found that greenhouse technology in the UK, particularly the use of automation, hydroponic and renewable energy sensors, significantly improved resource efficiency and agricultural productivity. The use of renewable energy technologies in greenhouses is proving to be different compared to research in other countries, demonstrating the UK's focus on reducing carbon emissions through a clean energy transition. These innovations have also increased crop yields by up to 30% and reduced water use by up to 50%, marking significant progress in sustainable agriculture.

This research makes an important contribution to the concept and application of digital technology in agriculture, especially in maximizing resource efficiency. The research methods used, such as the integration of automation sensor technology and renewable energy, offer new frameworks that can be applied in other agricultural sectors around the world. The limitations of the research lie in the lack of long-term data on the ecological impacts of the use of these technologies, particularly on biodiversity and the balance of local ecosystems. Further research should focus on the long-term evaluation and impact of the adoption of this advanced technology on the overall environment.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.
Author 4: Formal analysis; Methodology; Writing - original draft.

CONFLICTS OF INTEREST

The authors declare no conflict of interest

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