Strawberry Cultivation Using Smart Systems

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Abstract

In countries with advanced precision agriculture, IoT-supported monitoring and irrigation systems are widely used in strawberry cultivation. These systems monitor soil moisture, temperature, and humidity, offering remote access via ThingSpeak. Measurement reliability is validated with commercial meters, and user acceptance is high (over 80%) based on TAM surveys and interviews. Cloud-based systems, specifically Farm as a Service (FaaS) integrated systems, have been developed for comprehensive plant disease analysis and accurate prediction. These systems manage IoT devices, collect environmental and growth data, and perform analyses. The IoT-Hub network model ensures reliable data transfer even in harsh environments. This integration promotes widespread technology adoption in agriculture, enabling disease monitoring and prediction for strawberries, which fosters nature-friendly production. The need to preserve the quality of delicate strawberries drives farmers selling directly to consumers to adopt smart systems for product quality and health control. This has led to increased use of cloud-based smart irrigation and automation systems. In greenhouse strawberry cultivation, a new system uses an Arduino microcontroller, GSM module, and sensors to continuously monitor the environment and soil moisture. Users can control parameters via SMS, receiving notifications and activating the water pump when levels are exceeded. These systems provide effective remote greenhouse management. The study aims to enhance strawberry production efficiency, quality, and sustainability, optimize resource use, reduce costs through smart irrigation and climate control, and establish an environmentally friendly, data-driven production model.

Keywords: *Strawberry, Smart farming, remote sensing, Arduino, automation*

Introduction

The agricultural sector is confronted with a multitude of challenges on a global scale, encompassing population growth, climate change, water scarcity, and the sustainable utilization of natural resources. These issues are especially evident in the context of fruit cultivation, where production exhibits a high degree of sensitivity to environmental conditions. In this context, there is an increasing need to move beyond traditional agricultural methods and adopt more efficient, sustainable, and technology-driven solutions. In recent years, the integration of technologies such as the Internet of Things (IoT), remote sensing, artificial intelligence (AI) and edge computing into agricultural production has led to significant developments, particularly in the cultivation of high value-added products such as strawberries (*Fragaria x ananassa*). The strawberry (*Fragaria × ananassa*) is a widely consumed product, both in its fresh state and as a processed food, and has high economic value. However, the cultivation of strawberries is highly sensitive to various environmental factors, including temperature, humidity, soil moisture, diseases, and pests. Consequently, meticulous observation and prompt intervention are imperative throughout the production process. Smart farming systems have been shown to optimise production processes by enabling the real-time collection and analysis of environmental data, and the subsequent automatic decision-making processes based on this data (Kim et al., 2018; Zhang et al., 2021).

Varela-Aldás et al. (2024) conducted a study examining the adoption levels of IoT-based systems among different user groups. The study emphasized that user-friendly interfaces play a critical role in the success of such systems. This finding underscores the significance of technological infrastructure, as well as user training, trust in technology, and adaptability to local requirements. A significant challenge in the context of strawberry production pertains to the timely and accurate diagnosis of plant diseases. Kim et al. (2018) demonstrated the feasibility of early disease diagnosis through the utilisation of sensor data and machine learning algorithms. These systems empower producers to intervene in a timely manner, thereby reducing yield losses and minimising pesticide use, thus contributing to environmental sustainability. The approach proffers considerable benefits with regard to food safety. In the context of greenhouse strawberry production, effective irrigation management is of paramount importance.

As reported by Htet et al. (2021) and Angelopoulos et al. (2020), smart irrigation systems have the capacity to be automatically adjusted according to seasonal variability. Furthermore, these systems, when supported by edge computing technologies, have been shown to significantly reduce data processing times. Consequently, water resources will be utilised more efficiently, energy consumption will be significantly reduced, and production costs will be lowered considerably. Furthermore, these systems will empower producers to implement optimised irrigation strategies without the necessity for manual decision-making. In their study, Elenzano et al. (2021) examined how smart systems can provide solutions to the climatic challenges of strawberry cultivation in low-lying areas. The study, titled 'Smart Farming for Lowland Strawberry (*Fragaria x ananassa*) Production', was published in the academic journal. It was asserted that these systems optimise the production environment by monitoring microclimate conditions and enable stable production throughout the year. It is argued that this situation will also be extremely beneficial for countries such as Türkiye, which have different climate zones and the potential to geographically expand strawberry production. Moreover, Marques et al. (2024) conducted a study that demonstrated the potential of remote sensing technologies in the context of fruit orchards, offering insights into various aspects such as plant health, growth status, and yield estimation. These technologies facilitate the monitoring of extensive areas of strawberry fields, thereby enabling producers to make decisions at a macro level. The argument is made that tools such as satellite imagery, drone-based observation systems, and hyperspectral cameras can provide highly accurate information about the overall condition of production areas. The present paper offers a thorough evaluation of the utilisation of smart systems in strawberry cultivation, with particular reference to the extant literature. The effects of the integration of IoT-based monitoring systems, AI-supported disease prediction models, smart irrigation solutions and remote sensing technologies on production efficiency, sustainability and user acceptance will be discussed. Furthermore, an evaluation is conducted of the current state of strawberry production in Turkey and the potential for local adoption of these technologies. In this context, smart systems are regarded not only as a technological innovation but also as a strategic instrument for agricultural development and food security.

The Importance of Smart Agriculture In Strawberry Cultivation

The AgroTec 4.0 intelligent agricultural system was developed to enhance the efficiency of strawberry production in the Andean region of Ecuador. This system employs edge computing technology to optimise strawberry cultivation, particularly in greenhouse environments. The objective of this study was to evaluate the system's impact on efficiency by comparing strawberry production areas where AgroTec 4.0 was utilised and those where it was not, under the same greenhouse conditions. The system was designed with three key principles in mind: user-friendliness, cost-effectiveness and ease of implementation. These design principles were intended to ensure the system's suitability for use by low-income farmers who may have limited educational opportunities. Farmers who utilised the system observed a 15% increase in strawberry yield in their greenhouses. When the yield per square metre is considered, the control greenhouse yielded 5.0 kg per square metre, while the greenhouse using AgroTec 4.0 yielded 5.75 kg/m^2. Water usage was reduced by 20%. The control greenhouse utilised 80 litres of water per square metre, whereas the system reduced this to 64 litres. The system provides real-time decision support to farmers by analysing environmental data, including soil moisture, temperature, and light. The system's edge computing infrastructure processes data locally without sending it to the cloud, thereby reducing latency and eliminating dependence on internet connectivity. The system's adaptability to diverse production scales is facilitated by the use of low-cost sensors and a modular design. This study demonstrates how smart agriculture technologies can be an effective tool for sustainable agriculture practices, particularly in developing regions. AgroTec 4.0 has been demonstrated to contribute to environmental sustainability by increasing productivity and optimising natural resource use (Abdo-Peralta et al., 2024).

Strawberries are the most commercially produced and consumed fruit worldwide. Their production and consumption are increasing due to their unique aroma, taste and biochemical properties. The genus to which the strawberry belongs is Fragaria, which is itself part of the Rosaceae family, which is more commonly referred to as the 'rose family'. The provenance of the strawberry is traditionally attributed to South America, particularly Chile. It is evident that the wild F. vesca species is utilised by people residing in Asia, Europe, and America. In various geographical regions, including Japan, North China, Manchuria, Europe, Siberia, and America, there exist diverse eco-geographical areas in which alternative species are found to be concentrated. Despite its provenance in the Pacific Northwest region of North America, F. ananassa is now cultivated on a global scale. The strawberry (*Fragaria × ananassa*) is one of the most widely cultivated fruit species, grown in nearly every country, including high-altitude areas of tropical, subtropical and temperate climate zones. In this section, we aim to provide new perspectives on the future of strawberry cultivation techniques by analysing current academic studies on strawberry production (Marques et al., 2024).

Elashmawy and Uysal (2023) examined the use of machine learning models supported by data obtained from soil sensors in strawberry production within the scope of smart farming applications. They defined the second phase of a system that aims to predict the physicochemical properties of strawberries (e.g., colour and taste) at harvest time through the precise monitoring and management of soil conditions. The study involved the collection of real-time data from the soil of a commercial strawberry farm using sensor networks that had been installed for this purpose. These sensor networks were connected to cloud-based systems, which then analysed the data in order to predict the quality characteristics of the strawberries. In their work, they conducted analyses using both empirical and statistical methods, such as artificial neural networks and Gaussian process regression. The findings of the study indicated that when attempting to predict quality characteristics such as strawberry colour, either in isolation or in conjunction with soluble solid content (sweetness), the level of prediction accuracy achieved was 9% and 14%, respectively. This level of accuracy is pivotal for the establishment of a foundation for future data-driven soil management and optimisation of resources. This sustainability and automation system functions with fully automated soil conditioning mechanisms, thereby supporting sustainable and high-quality strawberry production. Machine learning algorithms are utilised to analyse soil data, with the objective of optimising decisions regarding factors such as the timing of harvest, the management of inputs, and the quality of the product. It has been demonstrated that such studies are not confined to the domain of strawberry production; rather, they can be readily adapted to other specialised crops. As data-driven decision-making processes become more widespread in agriculture, such systems offer significant advantages both economically and environmentally.

The efficacy of an edge computing and Internet of Things (IoT)-based smart farming system in combating diseases and environmental stress factors encountered in strawberry production was investigated. It is well established that strawberries exhibit a high degree of sensitivity to environmental changes, including temperature and humidity, as well as pests, due to their delicate structure. Consequently, pesticides and agricultural chemicals are utilised extensively during the production process. This scenario has the potential to exert a detrimental effect on both the quality of the product and the surrounding environment. The system utilised in the study performs processes such as the collection, analysis, prediction, and detection of diseases using edge computing technology. The IoT platform analyses environmental and plant data by combining different monitoring services into a single digital agriculture platform. The system facilitates low-energy data transmission over long distances by employing the LoRa communication protocol. Machine learning algorithms have been developed for the purpose of detecting outliers in data collected from the environment, thereby ensuring the reliability of the information provided to the user. The system utilises a computer vision model, based on the YOLO v5 architecture, to detect the seven most prevalent diseases in strawberries in real time. The accuracy rate of this model has been documented as 92%, which is considered to be highly effective in terms of facilitating early diagnosis and intervention. The system was subjected to empirical scrutiny through its implementation on a real strawberry farm. Consequently, the implementation of the application has yielded a number of advantageous outcomes, including the facilitation of early disease diagnosis, the mitigation of environmental stress, and the enhancement of production efficiency. It was also observed that the system's modular design facilitates its adaptation to diverse climatic and production conditions. This study demonstrates the efficacy of smart agriculture technologies in the cultivation of sensitive crops such as strawberries, thereby contributing significantly to environmental sustainability, productivity, and food safety (Cruz et al., 2022). The mounting global demand for food in agriculture gives rise to the need for innovative applications in terms of environmental sustainability and efficiency. In this context, although there has been success in the application of artificial intelligence (AI) technologies in areas such as plant stress detection and growth monitoring, research in the field of growth stage classification in special products such as strawberries has not yet been sufficiently extensive. An AI-based system, designated SmartBerry, has been developed to accurately classify growth stages and refine nutrient management in strawberry cultivation. The primary objective of the system is to accurately identify the different growth stages of the strawberry plant and to meet the specific nutrient requirements of each stage in a timely manner. This approach is critical for both increasing yield and improving fruit quality. The primary deficiencies identified by researchers in the extant literature pertain to the following: the absence of readily available and high-quality data sets, the utilisation of obsolete methodologies, the paucity of model comparisons (benchmarking), and the dearth of data sets and methods. In order to address these shortcomings, a high-quality image dataset has been created, covering seven different growth stages in a greenhouse environment. This dataset, collected under a range of light and environmental conditions, provides a substantial resource for model training. In the study, a range of deep learning models were evaluated, and the EfficientNetB7 model was identified as the most accurate, achieving an accuracy of 83.7%.

As a result, it clearly demonstrates the potential of AI-enabled systems to optimise nutrient management in strawberry farming. The importance of nutrient management The paper emphasises that nutrient management is a fundamental element in modern agriculture. Plants have different nutrient needs at each growth stage and meeting these needs at the right time directly affects both crop quality and soil health. While over-fertilisation degrades soil structure, under-fertilisation leads to economic losses. Therefore, stage-specific and timely nutrient application is indispensable for sustainable agriculture (Darlan, et al., 2025).

This review article comprehensively examines the most recent developments in this field, focusing on deep learning techniques used in strawberry cultivation, especially in greenhouse environments. The strawberry (*Fragaria × ananassa* Duch.) is widely regarded as the 'queen of fruits'. It is considered beneficial for cardiovascular health and has been shown to assist in balancing blood sugar levels due to its high vitamin C and antioxidant content. Its consumption is pervasive on a global scale, primarily due to its nutritional value, flavour and affordable cost. The text draws attention to the importance of precision agriculture practices, which have been demonstrated to provide higher yield and quality in comparison to traditional agricultural methods. In this context, the integration of deep learning models, such as convolutional neural networks (CNNs), which are extensively utilised in the domain of computer vision, into strawberry agriculture has been demonstrated to enhance production processes, rendering them more efficient and sustainable. However, the authors emphasise that a comprehensive and systematic review of deep learning applications in strawberry agriculture is absent from the extant literature. The following aspects are discussed in detail: the application of deep learning models in strawberry agriculture; the success of these models in applications such as growth stage classification, disease detection and maturity detection; and the improvement of models through fine-tuning techniques. The characteristics and limitations of the data sets used are also examined. Moreover, the challenges faced by research models in real-time applications, and the manner in which these challenges can be surmounted, are also discussed (Yang and Kim, 2023).

In the context of horticultural production, particularly in the domains of plant phenotyping (the measurement of plant characteristics) and management processes, the utilisation of remote sensing (the acquisition of information about the environment through electromagnetic or infrared energy) and machine learning (the process through which machines can learn or improve their performance through experience) holds particular significance. These technological advancements have had a substantial impact on the cultivation of cherries. In the domain of plant breeding and agricultural management, a substantial impediment has been identified in the necessity for expeditious and precise measurement of plant characteristics. The acquisition of data pertaining to substantial plant populations is of paramount importance for the purposes of monitoring plant health and conducting genetic analysis. At this juncture, state-of-the-art phenotyping technologies, remote sensing and machine learning are providing significant benefits. It has been posited that the integration of a range of sensor types (e.g. high-resolution RGB, multispectral, hyperspectral, chlorophyll fluorescence and LiDAR) in conjunction facilitates the evaluation of various morphological, structural, biophysical and biochemical characteristics.

Concurrently, the fields of computer vision and machine learning have witnessed the development of sophisticated methodologies for the extraction of significant biological information from such image data. The primary domains in which remote sensing and machine learning technologies are employed in the context of strawberry agriculture are delineated as follows: The detection of fruit and flowers, the assessment of maturity, quality, and intrinsic fruit characteristics, the analysis of fruit shape and yield prediction, the characterisation of leaf and vegetation characteristics, the identification of water stress, the detection of diseases and pests, and their classification, provide a framework of significant importance to strawberry producers and researchers. This framework enables the optimisation of the production process and the monitoring of plant health. The subsequent discussion encompasses prospective research opportunities and directions, with the objective of facilitating more widespread and effective utilisation of these technologies in the context of strawberry agriculture. In particular, the development of artificial intelligence-supported decision support systems, automation of data collection processes and the dissemination of real-time monitoring systems are identified as the primary areas that will facilitate digitalisation in strawberry agriculture (Zheng et al., 2021).

The use of Internet of Things (IoT)-based technologies to increase productivity and sustainability in strawberry farming has been introduced in many countries. The limitations of traditional farming methods, especially problems such as climate change, decreasing water resources and lack of labour force, push farmers to seek more innovative and technological solutions. In this context, smart agriculture applications are of great importance, especially in the production of sensitive fruits such as strawberries. The integration of IoT devices (soil moisture sensors, temperature and light sensors, automatic irrigation systems, etc.) into strawberry orchards is being addressed and farmers can remotely monitor and manage their agricultural activities with real-time data. Thus, water and fertiliser use is optimised, early detection of diseases is possible and overall product quality is improved. The results of an IoT-based system piloted in a specific region can also be shared. It can be stated that this system provides 20-30% higher yields compared to traditional methods, reduces water consumption and reduces the need for labour. Recent studies emphasise the importance of digital transformation in strawberry agriculture and show how IoT technologies can revolutionise agricultural production (Sari, et al., 2024).

A study conducted in Italy comprehensively investigates the effects of sensor-based fertigation management on resource use efficiency and crop performance in soilless strawberry cultivation. In the context of the mounting imperative for the sustainable utilisation of water and nutrient resources in agricultural production, this research offers a comparative analysis of the efficacy of sensor-assisted systems and conventional methods. In this research, a comparison was made of two different fertigation strategies in an open system hydroponic strawberry production in Italy. The first system is a traditional timer-based (TB) system, while the second is a sensor-based (SB) system. In the SB system, wireless sensors (Teros 12) were utilised to assess the moisture and electrical conductivity levels of the substrate (growing medium). The automation of irrigation and fertilisation decisions was enabled by the deployment of sensors, which facilitated the real-time monitoring of data and the subsequent determination of optimal intervention times. The findings indicate that the SB system utilised 38% less nutrient solution and 26% less total water in comparison to the TB system. This substantial reduction in resource consumption did not result in a decline in crop quality; in fact, total and marketable yields were higher in the SB system. This finding indicates that the utilisation of sensors in management systems confers benefits that extend beyond environmental sustainability, encompassing economic efficiency as well. Furthermore, the SB system demonstrated a 46% increase in water use efficiency and a 74% increase in nutrient use efficiency. The findings of this study demonstrate that the implementation of sensor-assisted fertigation can enhance the sustainability and efficiency of agricultural production, particularly in regions characterised by constraints in water and fertiliser resources. In conclusion, the study demonstrates that the implementation of sensor-based fertigation management in the context of soilless strawberry production confers substantial benefits, both in terms of environmental impact and economic efficiency. The dissemination of such technologies has the potential to make a significant contribution to the agricultural sector, particularly in addressing challenges such as climate change and water scarcity (Bonelli et al., 2024).

Recent research findings provide substantial evidence that the implementation of smart agricultural technologies in strawberry production is both effective in increasing productivity and significantly contributes to environmental sustainability. These technologies offer innovative solutions to the key challenges faced by traditional farming methods, including labour shortages, limited resources, disease management and climate change.

Results and Discussion

The implementation of smart farming systems has been demonstrated to result in a substantial enhancement in yield per square metre in strawberry greenhouses, with certain studies indicating an increase of up to 15%. This development is accompanied by notable economic advantages. Concurrently, it is possible to achieve savings of up to 20% in critical resources, including water usage. In particular, sensor-based fertigation systems have been shown to have the capacity to significantly reduce nutrient solution and water consumption, while concomitantly increasing productivity without compromising product quality. This approach offers significant benefits, including enhanced environmental sustainability and reduced input costs for farmers.

These systems provide farmers with real-time decision support by means of instant analysis of environmental data, including soil moisture, temperature and light. Machine learning models, supported by data from soil sensors, have been shown to be capable of predicting physicochemical properties of strawberries, including colour and sweetness, with a high degree of accuracy at the point of harvest. Consequently, the timing of harvesting and the management of product quality can be optimised to increase market value.

Furthermore, edge computing and Internet of Things (IoT) based systems have been demonstrated to possess the capability to detect common diseases in strawberries with a high degree of accuracy. The implementation of this early detection capability has been demonstrated to result in a reduction in the utilisation of pesticides, thereby enhancing the quality of crops and reducing the environmental impact. The processing of data locally by such technologies has been demonstrated to reduce latency and eliminate reliance on internet connectivity, rendering them particularly suitable for farmers in rural and infrastructure-limited areas.

The integration of deep learning models and artificial intelligence has demonstrated significant success in domains such as the classification of the growth stages of strawberries, the detection of diseases, and the determination of fruit maturity. The utilisation of remote sensing and machine learning techniques has proven to be a versatile approach, finding application in a multitude of domains. These include, but are not limited to, the identification of fruit and flowers, the estimation of crop yield, the assessment of water stress, and the identification of diseases in agricultural settings.

A number of recommendations stand out for the sustainability and popularisation of progress in this area:

Technology Dissemination and Accessibility: It is of great importance that the developed user-friendly, economical and easily applicable systems are made available to farmers, especially those with low income and limited education. In this direction, adoption of technology should be accelerated by developing government supports, training programmes and appropriate financing models. The use of technologies such as edge computing can enable smart agriculture applications to become widespread even in regions with inadequate internet infrastructure.

Enrichment and Standardisation of Data Sets: For AI models to be more robust and generalisable, larger, diverse and high quality image and sensor datasets covering different climatic conditions, geographical regions and strawberry varieties need to be created. Future work should focus on creating common databases to facilitate the sharing of these datasets.

Continuity of Model Development and Integration: Continue to develop more complex and customised deep learning models for different growth stages, physiological stress states and disease symptoms of strawberries. By integrating data from different types of sensors, more comprehensive plant monitoring systems should be created, laying the foundation for autonomous agricultural robots and UAV-based spraying systems.

The development of real-time decision support systems: The development and dissemination of AI-enabled decision support systems should be accorded priority. These systems have the capacity to facilitate immediate and optimised decision-making processes by farmers, pertaining to issues such as soil moisture, nutrient requirements, disease risk and harvest timing. The development of integrated systems with fully automated soil conditioning mechanisms is recommended for the purpose of sustainable and high-quality strawberry production.

Increasing Economic and Environmental Impact Analyses: It is recommended that further studies be conducted on the long-term economic returns and environmental benefits (water savings, fertiliser and pesticide reduction, carbon footprint reduction) of smart farming systems. Such studies would be more comprehensive and transparent. Evidence of this nature would be persuasive to farmers and policymakers, encouraging widespread adoption of technologies.
These recommendations provide a roadmap to fully realise the potential of digital transformation in strawberry agriculture and ensure a sustainable, efficient and profitable production process.

Declaration of Competing Interest
The authors report no declarations of interest.

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