



Real-time greenhouse management using IoT, digital twin, and augmented reality for optimal control and decision-making

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ABSTRACT

This article investigates the integration of the Internet of Things (IoT), digital twin (DT), and augmented reality (AR) technologies to advance digital services in the management, monitoring, and control of agricultural greenhouses, addressing the sector's technological demands. By leveraging advanced technologies, this research aims to enhance efficiency across various fields, including industry, logistics, and commerce. The core objective is to develop a prototype IoT system, incorporating DT and AR, to create a digital transformation environment. This system provides real-time visualization and monitoring of sensor data from physical IoT devices, enabling user interaction and control through microcontroller-based sensor nodes installed in the greenhouse. Data transmission is achieved using the MQTT protocol, while an AR application facilitates greenhouse visualization and control. The findings demonstrate the system's effectiveness in enabling real-time communication between IoT devices and the AR application, with users successfully performing tasks without prior experience, thereby validating the system's usability and efficiency.

Section: RESEARCH PAPER

Keywords: IoT; augmented reality; digital twin; real-time monitoring; greenhouses; sensor data

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1. INTRODUCTION

Maximization of agricultural production, resource efficiency, and environmental stewardship are the central goals of modern farming practices, which emphasize the significance of greenhouse control and management. With respect to the issue of coping with the dynamic and intricate characteristics of environmental elements involved in plant growth, traditional methods of managing a greenhouse have failed at times. Combined with new technologies like digital twin technology (DT), augmented reality (AR), and the Internet of Things (IoT), greenhouse management is able to embrace a new philosophy towards real-time monitoring and decision-making. The IoT sensors are central to deploying these technologies as they enable sensor nodes to get and transmit environmental data in real-time. IoT sensors are deployed to measure critical parameters like temperature, humidity, light intensity, soil moisture, and CO₂ concentration. They offer a vast data set required for effective greenhouse management. The uninterrupted data flow offered by IoT technology allows

greenhouse conditions to be dynamically controlled to maximize crop growth and resource use. Through the creation of virtual twins of actual greenhouses, digital twin technology significantly improves greenhouse management. In a risk-free virtual world, managers are free to try, test, and improve different management practices using these interactive digital twins. Stakeholders can improve the productivity and robustness of greenhouse operations by utilizing these virtual images to conduct predictive analysis, predict potential problems, and take proactive steps to mitigate risks.

However, despite the increasing interest in integrating IoT, Digital Twin, and AR technologies in agriculture, the literature lacks a unified, real-time system that effectively combines these three components for greenhouse management. Existing studies often treat these technologies in isolation or in pairs, missing the synergistic potential of their full integration. This research addresses this gap by proposing a novel, real-time framework that tightly couples IoT-based sensing, Digital Twin

simulation, and AR-based visualization into a cohesive decision-support system for greenhouse operators.

These technologies are complemented by AR, which offers an interesting and interactive data display interface. AR allows real-time visualization of sensor readings and environmental variables, facilitating the presentation of complex information. With this immersive experience, farmers and greenhouse managers can make better decisions by being able to rapidly analyze data, recognize trends, and apply accurate control measures to ensure the best conditions for growth. This paper discusses how IoT, DT technology, and augmented reality may be merged to further augment sustainable agriculture practices and transform the management of greenhouses. Major adoption impediments to farm technology, such as data complexity, system interoperability, and user involvement, are overcome by the convergence of multiple technologies. This project aims to demonstrate how these technologies can be utilized in combination to enhance greenhouse management, enhance resource utilization, and promote environmental sustainability by developing a dynamic IoT control and visualization system. The novelty of this work is the real-time, multi-tiered integration of IoT, Digital Twin, and AR technologies into a single operating process. Unlike other current approaches, which are likely to focus on data acquisition, simulation, or visualization separately, our system delivers continuous environment monitoring, dynamic twin modeling, and interactive AR feedback within an integrated framework. This comprehensive strategy supports not just best-of-class decision-making but also native user behavior, eliminating the ongoing problems of system fragmentation and low user involvement in existing solutions. Therefore, the main objectives of this study are: (1) to design and implement a real-time, integrated system with IoT-based sensing, Digital Twin simulation, and Augmented Reality visualization for monitoring and controlling greenhouses; (2) to verify the ability of the system to optimize the environmental conditions and the resource consumption by dynamic data interaction; and (3) to enhance user interaction and decision-making via a simple AR interface. By achieving these objectives, this work aims to overcome the weakness of fragmented and disconnected strategies, offering a holistic approach that promotes operational transparency and promotes sustainable agriculture by means of digital innovation.

The paper is organized as follows: Section 2 reviews related work, while Section 3 presents the materials and methods, including the conceptual framework, IoT devices, design approach, system architecture, AR interface, and experimental design. Section 4 discusses the results and analysis, followed by a discussion in Section 5. Finally, Section 6 concludes the paper with a summary and future work.

2. RELATED WORK

Digital twin technologies, augmented reality, and Internet of Things sensors have all played significant roles in advancing greenhouse management. The accuracy of climate control in greenhouses can now be enhanced using IoT sensors and real-time data analysis, which continuously measure and adjust environmental conditions such as temperature, humidity, light intensity, soil moisture, and CO₂ levels [1], [2], [3], [4]. The integration of machine learning algorithms in such sensors optimizes the greenhouse environment to achieve higher crop growth efficiency and yield and lesser resource wastage [2]. Cloud-based analytics platforms also deal with big streams of

IoT sensor data, providing rich insights to guide operational strategy. This leads to increased agricultural productivity, resource-use efficiency, and forecastability of crop growth. Additionally, IoT sensors facilitate automated responses to instantaneous environmental shifts, safeguarding crops and initiating a new era of precision agriculture that is better for the planet as well as the bottom line [3]. Augmented reality (AR) technology has proven itself to be a vital tool in greenhouse cultivation, enabling numerous benefits in decision-making for optimal. AR provides real-time visualization of the environmental conditions inside greenhouses to enable farmers to monitor microclimate fluctuation and make decisions according to temperature and humidity [5]. Interfaces like ARCHIE2 conserve crew time and labor in greenhouses by facilitating less manual labor and greater focus on plant growth and scientific experiments [6]. The use of AR in agriculture supports decision-makers in visualization of plant growth and development modeling, evaluating adaptation scripts for managing farming lands and improving planning for sowing to achieve high plant yields through scientifically based zoning of land areas [7], [8]. Besides, AR apps, such as the proposed greenhouse data acquisition system with MQTT protocol and Unity for Android mobile phones, have interactive features that assist in enhancing the virtual lab experience and showing comprehensive information regarding greenhouse parameters like soil humidity, temperature, ambient humidity, and carbon dioxide level [9]. The integration of DT technology and augmented reality in managing greenhouses comes with various advantages, including instantaneous observation of environmental conditions and better decision-making. Digital twins generate digital representations of physical items like crops and lands [10], [11], while the integration of digital twins and real-time overlay of data over camera pictures allows farmers to imagine and study green microclimate fluctuations [12]. This technology provides reliable monitoring of plant status, timely detection of nutrient deficiencies and crop diseases, and anticipatory decision-making to efficiently manage the crops [13]. Furthermore, the use of augmented reality through digital twins allows for interactive visualizations of data, scenario modeling, and experiential behavior, enhancing understanding of intricate systems and facilitating rapid interpretation of solutions in agriculture and environmental sustainability [14]. The joint application of IoT sensors, AR, and DT technologies significantly enhances the control of greenhouses with real-time monitoring, precise environmental management, and decision-making. The three technologies together enhance better agricultural productivity, resource use, and sustainable agriculture [15].

This paper proposes a technical solution that combines these technologies to create a comprehensive digital environment for greenhouses, enabling a new paradigm of intelligent and efficient agricultural management. Table 1 provides a comparative overview of related AR-based studies, highlighting their application domains, objectives, technologies, and integration levels. The limitations identified in the literature and their corresponding proposed solutions are succinctly summarized in Table 2.

Table 1. Positioning our AR-IoT-Digital Twin framework within the landscape of smart agriculture: a comparative overview of related works.

Criterion	Study [16]	Study [17]	Study [18]	Study [19]	Study [20]	Study [21]	Study [22]	Our Study
Application Domain	Environmental Education	Livestock Farming	Agriculture (Berry)	Agriculture (Strawberry)	Agriculture (Safety)	Precision Agriculture	Precision Farming	Agriculture (Greenhouses)
Main Objective	AR Ecology Education	Wearable AR Animals	AR Berry Thinning	AR Strawberry Ripeness	AR Safety Education	AR Plant Disease	AR Crop Monitoring	AR real-time Greenhouse monitoring
Technologies	AR	AR	AR, DL	AR, YOLOv7	AR	AR, DL	AR, IoT	AR, DT, IoT
Level of Integration	High-Interactive AR	Medium (AR tested)	Medium (Field Tested)	Low (Tested)	Medium (Tested)	Low (Tested)	High (Tested)	High (Tested)
Experimental platform	Campus butterfly garden	On-field & Laboratory	Field Test	Field Test	Tested ARISE	On-field	Real environment	Prototype Test
Participants	60 students	18 participants	2 expert farmers	Not Specified	21 participants	Not Specified	10 farmers	19 participants
User Interaction	Smart phones / tablet	SmartGlove	Microsoft HoloLens	Microsoft HoloLens 2	VIO in iOS device	MOVERIO BT-350 AR	Camera	Android camera
AR Visualization	Virtual Garden	Animal Data	Berry Thinning	Representation of the ripeness level	Farm Safety AR	Plant Disease AR	Dynamic indoor planting	Managing greenhouses in AR real time
Communication Protocol	GPS, 3G Network	RFID, Bluetooth	LTE mobile wifi	Not Specified	Not Specified	AWS-IoT, MQTT	IoT, WSN	MQTT, IoT
Field (Greenhouse)	Yes	No	No	Yes	No	No	No	Yes

3. MATERIALS AND METHODS

3.1. Conceptual Framework: IoT, DT, and AR

In our approach, we integrate key concepts of the IoT, DT, and AR to enable management and visualization in agriculture. This integration is aimed at achieving improved operational efficiency, decision-making, and user interaction in greenhouse systems. Digital twins are virtual representations of physical objects or systems that offer real-time monitoring, simulation, and data visualization.

In our environment, DTs replicate greenhouse conditions digitally, offering a window into operational conditions and

data-informed decision-making. The virtual models are tightly coupled with physical systems, enabling accurate tracking and control. AR, by contrast, generates an immersive interface by superimposing digital information onto the physical environment. It facilitates interaction with real-time sensor data, making system conditions and alerts palpable through intuitive visual overlays. This integration of virtual and real-world data enhances the users' comprehension and responsiveness. IoT technology forms the backbone of data collection in our system. It enables interaction among smart devices - physical objects embedded with sensors and assigned distinctive IP addresses. The devices continuously collect and transmit environmental data, which is then processed and made perceivable by DT and AR modules.

By combining IoT, DT, and AR technologies, we present an interactive control and reporting system for agricultural transformation. IoT enables real-time data acquisition, DT offers virtual simulation and modelling, and AR enhances user experience through interactive visualization. This combined solution can revolutionize greenhouse operations by increasing efficiency, reducing energy consumption, and extending system longevity. An overview of the key elements of the system is illustrated in Figure 1.

3.2. IoT Devices

The primary objective of developing the node-IoT system was to design hardware capable of efficiently monitoring, collecting, and controlling physical parameters, while also being cost-effective and energy-efficient. As shown in Figure 2, the hardware board is composed of four main modules: a microcontroller, a set of sensors and actuators, an energy module, and a wireless communication module. These components work together to form a robust and adaptable system for greenhouse monitoring and management. Figure 2 presents the PCB layout of a temperature and humidity sensing node, specifically designed for indoor greenhouse environments. In our implementation, we used seven different

Table 2. Summary of literature limitations and proposed solutions.

Limitations of Literature	Solutions Provided by the Proposed System
Lack of real-time monitoring and decision-making	IoT sensor integration enables real-time analytics and continuous data collecting, allowing for dynamic environmental parameter control in greenhouses.
Inadequate data visualization and user interface	Using cutting-edge AR technology to deliver a natural and engaging user interface for the real-time viewing of sensor data and ambient conditions.
Limited ability to simulate and optimize management strategies	Implementation of Digital Twin Technology to create virtual replicas of greenhouses, allowing for simulation, analysis, and optimization of management strategies in a risk-free virtual environment.
Scalability and sustainability issues	Development of a scalable and sustainable system through software upgrades, reducing the need for complex hardware replacements.
Dependence on single connectivity options	Provision connectivity options, including WiFi, to ensure reliable functionality using local and cloud servers.
Lack of mobility and wearability in AR solutions	Utilization of smartphones for AR applications, making the technology accessible and convenient for all users, eliminating the need for specialized wearable hardware.

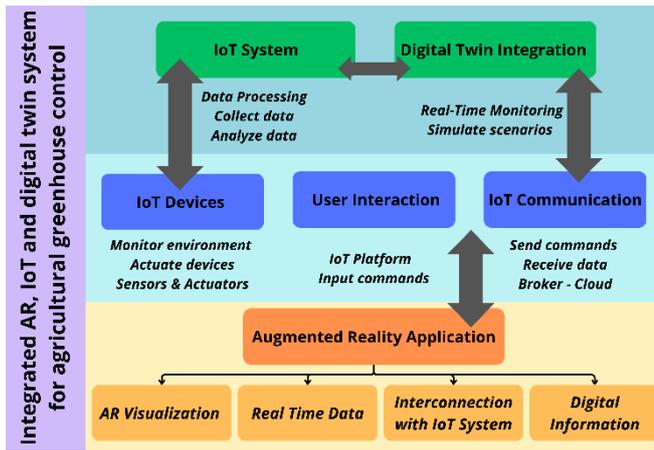


Figure 1. Proposed system diagram.

sensors to measure various environmental parameters both inside and outside the greenhouse, ensuring high measurement accuracy. The sensors and actuators are controlled by a program running on the ESP8266 microcontroller. Data communication is carried out using the MQTT protocol, supported by the PubSub-Client library. This setup enables reliable and efficient data exchange between the IoT nodes and the central system. The core infrastructure includes an IoT platform built on Node-RED, with data streams managed through the HiveMQ cloud service. This platform handles the storage, processing, management, and visualization of the collected data, ensuring smooth integration and efficient operation of the greenhouse management system.

3.3. Iterative Design

We used an iterative design approach that combined abstract and presentation design techniques to create the agricultural greenhouse application. This methodology facilitated the ongoing enhancement and verification of the program via user input and real-world experimentation. The iterative design phases are shown in Table 3, which also emphasizes the contributions made by the presentation and abstract designs at different stages of the development process.

3.4. Architectural Design of the Proposed System

The intersection of Internet of Things, Digital Twin technology, and Augmented Reality in greenhouse management is a major breakthrough in the agriculture sector. The interdisciplinary approach facilitates real-time monitoring and decision-making with a more holistic approach to modern greenhouse operations. IoT technology, equipped with a plethora of sensors - like Bragg, piezoelectric, electrochemical, electromagnetic, and fibre-optic sensors - is transforming the way important environmental parameters like temperature, humidity, and light are being sensed. The accurate data obtained with these sensors assist farmers in optimizing the development of the crops as well as the utilization of resources with utmost efficiency. Ongoing monitoring keeps the optimal conditions for growing in line, and therefore plant growth and overall yield are improved [2], [23]. AR technology also improves decision-making by allowing real-time monitoring and access to contextual, in-depth knowledge about greenhouse regulation [24]. It offers convenient-to-use visual overlays that support interaction with live sensor data and system status. Digital twin technology further enhances this platform with predictive and sustainable management capabilities. It creates a virtual model

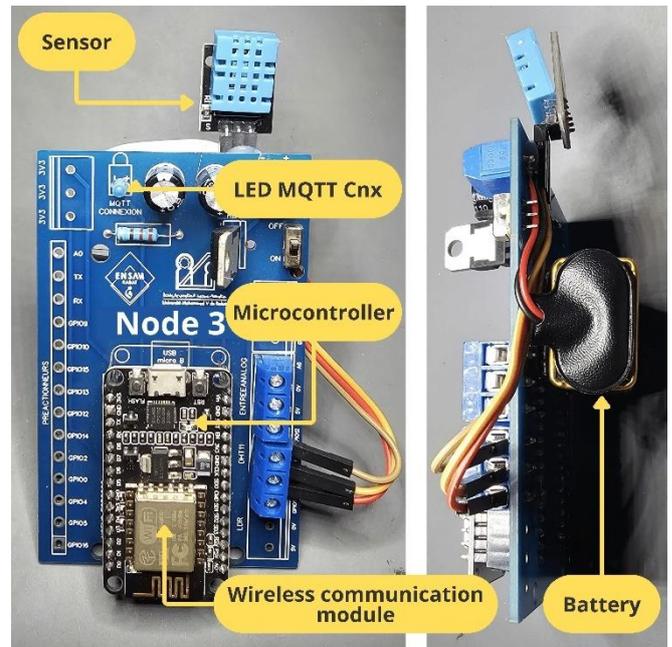


Figure 2. Exemplary Sensor Node for Monitoring Greenhouse Interior Temperature and Humidity.

of the greenhouse conditions to support simulation and data-driven approaches to irrigation, fertilization, and pest control. They depend on real-time data regarding the properties of soil, plant physiology, and the level of nutrients [25]. Intelligent control at this level facilitates precise nutrient supply and efficient environmental control, thereby pushing sustainable agriculture practices. Notwithstanding these challenges of the full implementation of these technologies, digital twin technology holds robust potential for reducing the cost of energy and redesigning conventional energy management in the case of greenhouses. The integration of IoT sensors - such as smart stick sensors - into smart devices gives valuable feedback

Table 3. Iterative design process for agriculture greenhouse application.

Design Phase	Abstract Design	Presentation Design
Project Software and Hardware	Does not rely on specific software and hardware requirements.	Relies on the project's specific software and hardware configurations.
Storyboard Creation	Develop a storyboard to illustrate the application's user flow and functionalities.	Create a working prototype of the application with full functionality for potential users.
User Interaction Testing	Provide the storyboard to greenhouse operators to gather initial feedback.	Allow potential users to interact with the prototype in a real greenhouse environment to gather detailed feedback.
Usability Notes and Fixes	Note usability issues based on storyboard feedback and address them in the application design.	Record and fix usability issues observed during prototype testing to enhance user experience and functionality.
Target User	Greenhouse operators involved in greenhouse management.	Greenhouse operators who will interact with the application in a real environment.
Focus	High-level design and conceptual validation.	Practical usability and functionality validation under real-world conditions.
Iteration	Initial design iteration based on conceptual feedback.	Subsequent design iteration based on practical, hands-on feedback.

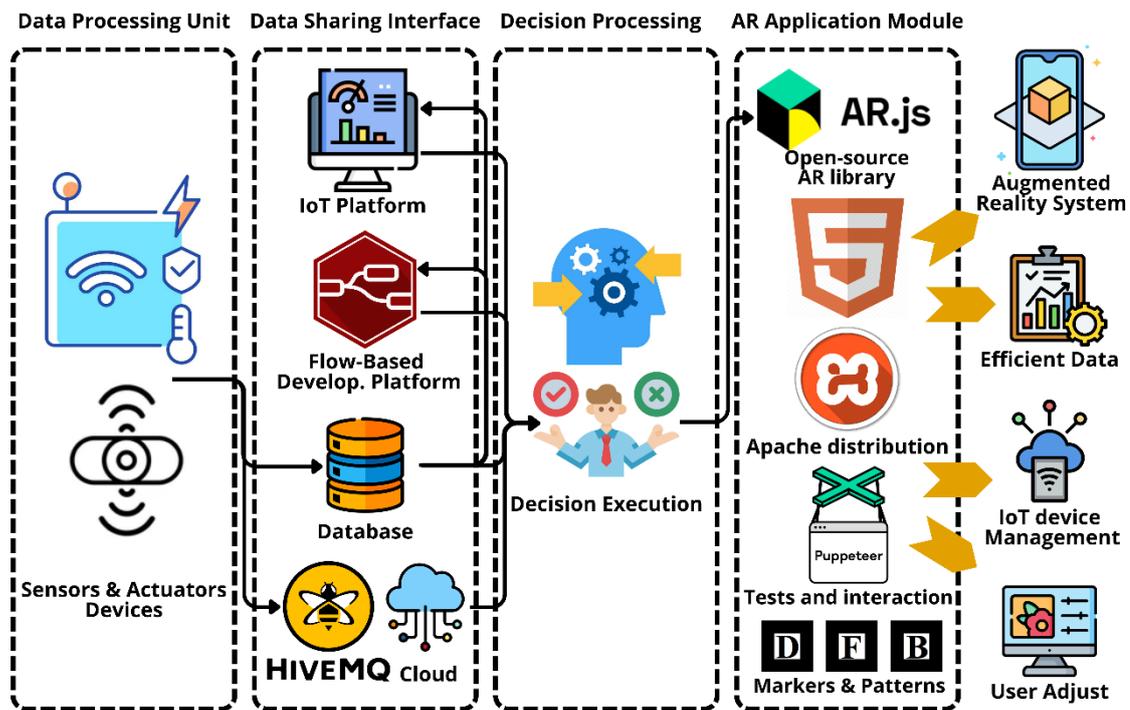


Figure 3. The specifications of the components identified for the proposed solution.

on critical parameters such as temperature and soil moisture, further improving operational decision-making. In the future, additional research will be required to surpass the current limitations and expand the range of applications of these technologies for greenhouse operation. Continued innovation will assist in delivering improved agricultural productivity and more sustainable operations. The integration of AR in greenhouse management introduces a new paradigm to decision-making. Advanced 3D modelling platforms such as Unity and Unreal Engine 5 allow the development of detailed Building Information Models (BIM) and realistic plant models for AR applications. Tools like the Perpetual Garden App and botanically accurate 3D models enhance educational experiences and museum exhibits. Furthermore, immersive technologies - including VR headsets, Geographic Information Systems (GIS), and AR Holodeck software - enable rich visualization of plant data.

Combined with IoT sensors that provide real-time feedback on environmental conditions, AR technology significantly enhances greenhouse management by offering intuitive and interactive monitoring tools [26]. Figure 3 presents the specifications of the components selected for the proposed solution.

3.5. Augmented Reality Interface

This section presents the development of an AR application designed to enhance user interaction through immersive, real-time experiences. Built using AR.js and accessible via standard smartphones, the application allows users to visualize complex data collected from digital sensors. These data are represented in multiple formats, including dynamic graphs, real-time gauges, and precise numerical displays. A key feature of the application is its ability to control IoT-connected actuators using virtual buttons, which are overlaid on physical markers. This interactive control interface is illustrated in Figure 4. The development process involved detailed screen design and the integration of

advanced AR controllers to ensure smooth user interaction. One of the core capabilities of the application is its use of pattern marker tracking and detection. This technology enables virtual objects to be accurately placed and maintained within the physical environment, improving both engagement and operational control, particularly in agricultural and environmental monitoring contexts. The AR application is built using A-Frame, a web framework for virtual reality, in combination with AR.js, a JavaScript library for augmented reality. The HTML structure defines a scene in which the device's webcam detects a specific marker pattern (pattern-

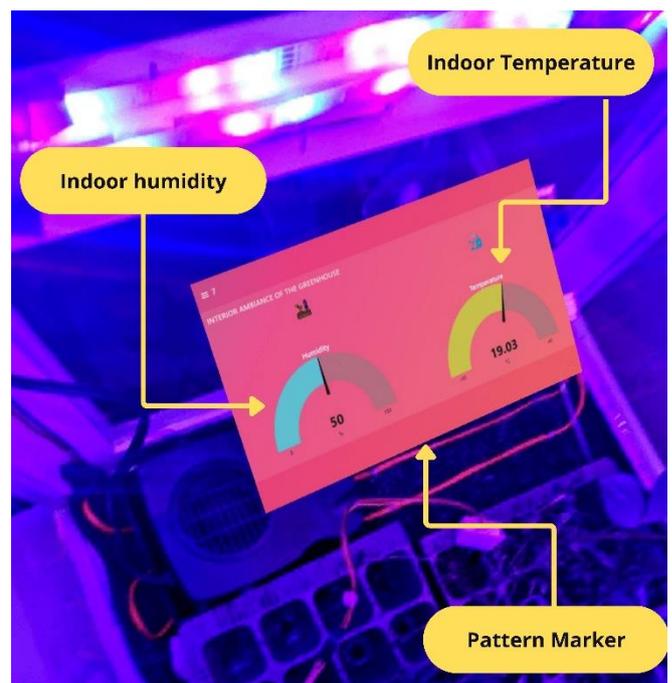


Figure 4. Integrated augmented reality interface for IoT sensor visualization.

x.pat). When this marker is recognized, a virtual plane (<a-plane>) appears in the scene and dynamically displays an image (Testcapture.jpg), contributing to the immersive visualization experience.

Key functionalities include:

- **Marker Detection and Tracking:** Utilizing AR.js's marker-based tracking, the application identifies and tracks the predefined marker pattern in real time, ensuring accurate placement and interaction of virtual content.
- **Dynamic Image Display:** The <a-plane> element is configured to display the image dynamically. An animation sequence animates the image's position from (0, 0, 0) to (4, 0, 0) upon marker detection, enhancing user engagement through seamless content transitions.
- **Real-time Updates:** The application periodically updates the displayed image using JavaScript (updateImageSource() function), ensuring that the visual content remains current and relevant during user interaction.

The developed AR application successfully integrates A-Frame and AR.js to deliver an immersive and responsive user experience. The precise marker detection and fluid animation enhance user interaction, providing a seamless transition between physical and virtual environments. The periodic image updates maintain the application's relevance and usability, catering to evolving user needs and application requirements. Techniques such as requestAnimationFrame and efficient image caching are employed to optimize rendering performance, ensuring smooth animation and responsiveness. A-Frame and AR.js's compatibility with major web browsers and mobile devices enhances accessibility and usability across diverse platforms, expanding the application's reach and usability.

3.6. Theoretical Tools for Vision-Based Localization in AR

Vision-based localization for augmented reality is founded on a set of theoretical tools developed to address two basic issues that are inherent in camera-based positioning systems. The first issue is camera calibration, i.e., the task of accurately representing the camera and computing its internal parameters. This is a prerequisite for determining the correspondence between 2D image coordinates and the corresponding 3D real-world structure. Reliable calibration ensures that visual data captured by the camera is correctly interpretable in spatial terms. The second problem is camera pose estimation, or the estimation of the camera pose with respect to a world reference frame. Pose estimation is needed for alignment of virtual objects and real-world features in AR systems to ensure coherent and stable overlays during interaction. Over the past decades, extensive research has been conducted in both domains, leading to robust mathematical models and algorithmic frameworks. These include pinhole camera models, distortion correction techniques, Perspective-n-Point (PnP) algorithms, and filtering methods such as Kalman filters or optimization-based approaches. Together, these tools form the foundation for precise and reliable localization in AR applications.

Camera modelling is a prerequisite to calibration, as it defines the image formation process and establishes the analytical relationship between a 3D point in the object space and its corresponding 2D projection in the image plane. This relationship is governed by a projection matrix that encapsulates both the intrinsic and extrinsic parameters of the camera. Initially, the pinhole camera model is adopted as a classical

approach, which is then extended to incorporate radial and tangential lens distortions for a more accurate representation of real-world optical systems. The pinhole model uses linear transformations to project a 3D point from the world coordinate system to the image plane, representing the core of classical camera modelling. The following Equation (1) is the projection model that is used to transition from a point in the world frame (R_O) to the estimate frame (R_i)

$$p_i = M_{int} \cdot M_{ext} \cdot P_0 \quad (1)$$

with p_i : image coordinates in the camera frame R_i , M_{int} : Intrinsic parameters, M_{ext} : Extrinsic parameters, P_0 : Coordinates of the object in the world frame R_O . It can be written in the following matrix form Equation (2):

$$\begin{pmatrix} U \\ V \\ 1 \end{pmatrix} = \begin{pmatrix} K_u & S_{uv} & U_0 \\ 0 & K_v & V_0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \cdot \begin{pmatrix} R_{C/O_{11}} & R_{C/O_{12}} & R_{C/O_{13}} & t_x \\ R_{C/O_{21}} & R_{C/O_{22}} & R_{C/O_{23}} & t_y \\ R_{C/O_{31}} & R_{C/O_{32}} & R_{C/O_{33}} & t_z \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} X_i \\ Y_i \\ Z_i \\ 1 \end{pmatrix} \quad (2)$$

with U, V : Projected 2D coordinates, K_u, K_v : Scaling factors, S_{uv} : Skew coefficient, U_0, V_0 : the optical center, f : Focal length of the camera, R_{ij} : Elements of the rotation matrix $R_{C/O}$, t_x, t_y, t_z : Translation vector components, X_i, Y_i, Z_i : 3D coordinates of the point p_i .

Camera calibration is a fundamental step in AR systems relying on visual localization. It aims to accurately estimate both intrinsic and extrinsic parameters of the camera. These parameters form the camera projection matrix, which defines the transformation from 3D world coordinates to 2D image coordinates. Accurate calibration ensures precise alignment between virtual and real-world elements - a prerequisite for reliable AR experiences. Calibration involves solving of the projection matrix, derived from correspondences between known 3D points in the world frame X_i, Y_i, Z_i and their projected 2D counterparts U, V in the image plane. Optimization techniques are typically employed to minimize projection errors across a set of sampled point correspondences.

Two main methods are commonly employed for camera calibration in augmented reality systems: the Least Squares Method and Zhang's Method. The Least Squares Method (equation 3) is a classical approach that minimizes the reprojection error by adjusting the camera parameters to best match the observed image points with their corresponding known 3D world coordinates. It solves the projection equations using linear least squares optimization and typically assumes the absence of lens distortion. While this method is simple and computationally efficient, it may suffer from reduced accuracy in practical AR scenarios where lens distortion cannot be neglected.

$$\begin{pmatrix} X_i & Y_i & Z_i & 1 & 0 & 0 & 0 & 0 & -U \cdot X_i & -U \cdot Y_i & -U \cdot Z_i \\ 0 & 0 & 0 & 0 & X_i & Y_i & Z_i & 1 & -V \cdot X_i & -V \cdot Y_i & -V \cdot Z_i \end{pmatrix} \cdot C = \begin{pmatrix} U \\ V \end{pmatrix} \quad (3)$$

with

$$C = (m_{11}, m_{12}, m_{13}, m_{14}, m_{21}, m_{22}, m_{23}, m_{24}, m_{31}, m_{32}, m_{33})^T.$$

In contrast, Zhang's Method Equation (4) is a more robust and widely adopted technique that explicitly models both radial and tangential lens distortions. It is based on estimating planar

homographies from multiple images of a known calibration pattern (such as a checkerboard) viewed from different orientations. Assuming the calibration plane lies on $Z=0$, homographies are computed between the world plane and the image plane. These are then used to derive the intrinsic and extrinsic parameters of the camera. A nonlinear refinement step, typically bundle adjustment, is subsequently applied to improve calibration accuracy.

$$\begin{pmatrix} U \\ V \\ 1 \end{pmatrix} = M_{\text{int}} \cdot [r_1 \ r_2 \ r_3 \ t] \cdot \begin{bmatrix} X \\ Y \\ 0 \\ 1 \end{bmatrix} = M_{\text{int}} \cdot [r_1 \ r_2 \ t] \cdot \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} \quad (4)$$

with r_1, r_2, r_3 the columns of the rotation matrix.

3.7. Building and Implementation

A precise prototype was created employing certain hardware and software components to get ready for testing. This methodology guaranteed an accurate assessment of the prototype's functionality and performance. A thorough summary of the software tools and platforms used in this investigation, together with information on their versions and uses, is given in Table 4. Simultaneously, Table 5 lists the hardware specs and settings that users need in order to enable the prototype's optimal functioning.

3.8. Experimental Design

3.8.1. Participants Profiles and Selection Criteria

For the evaluation of the application of farming in a greenhouse, participants were selected in a mixed group to enable robust and stable findings. Participants were selected based on several factors like their experiences and backgrounds of working with technology and managing a greenhouse, to enable high dependability in usability evaluation. Nineteen participants in total took part in the study. This population was chosen deliberately to reflect a variety of technical skills and demographics applicable to the target application environment. Selection criteria were chosen to include individuals with varying levels of experience with greenhouse systems, IoT technologies, and AR applications.

3.8.2. Experimental Protocol and Testing Procedure

The testing procedures were placed in a controlled setting that replicated the circumstances seen in a prototype greenhouse. A systematic introduction to the program, complete with a feature and functionality demonstration, was given to each participant. The participants were given comprehensive instructions to help them navigate the many features of the program. After the practical testing phase, participants answered a series of

Table 4. Software requirements for prototype development.

No	Feature	Requirements
1	Operating System	Windows 10
2	Programming Language	JavaScript, HTML
3	IoT Platform	Node-RED
4	Tunneling Service	NGROK
5	Web Automation Tool	Puppeteer
6	Web Browser	Google Chrome
7	AR Development Library	A-Frame, AR.js
8	Code Editor	Visual Studio Code, Sublime Text
9	HTML/CSS Framework	Custom HTML for AR visualization

Table 5. Test device hardware configuration.

No	Feature	Requirements
1	Device	Smartphone Samsung Galaxy S23 Ultra
2	Operating system	Android
3	RAM	12GB
4	Storage	512GB Internal storage
5	Processor	Qualcomm Snapdragon 8 Gen 2 Octo-Core
6	Camera	200MP main sensor (with additional cameras)
7	Display resolution	3088 x 1440 (Quad HD+)
8	Technology main screen	Dynamic AMOLED 2X
9	Number of colours	16M
10	Refresh rate (main screen)	120 Hz

questions meant to evaluate their application experience as well as their demographic data. With this strategy, thorough input on the AR application's usability and efficacy in an actual agricultural scenario was guaranteed.

3.8.3. Assessment Tools and Measurement Methods

The assessment utilized a two-part questionnaire to gather relevant data. The first part collected demographic information, as detailed in Table 6, which includes variables such as gender, age, experience with greenhouse systems, familiarity with IoT technologies, and technical background. This demographic data was essential for understanding the participant profile and ensuring a representative sample. All participants were proficient in using mobile devices.

Table 6. Demographics of participants for AR greenhouse application study.

Item	Options	Frequency (n)	Percentage (%)
Gender	Male	16	84.2
	Female	3	15.8
Age	Under 20 years old	3	15.8
	18-29 years old	10	52.6
	30-39 years old	4	21
	40-49 years old	1	5.3
	Above 50 years old	1	5.3
Experience with Greenhouse Systems	Yes	1	5.3
	No	18	94.7
Familiarity with IoT Technologies	Yes	12	63.2
	No	7	36.8
Experience with AR Applications	Yes	0	0
	No	19	100
Technical Background	Engineering/IT	14	73.7
	Agriculture/Greenhouse	2	10.5
	Other	3	15.8
Frequency of Greenhouse Use	Daily	1	5.3
	Weekly	0	0
	Monthly	0	0
	Rarely	0	0
Comfort with Technology	Never	18	94.7
	Very Comfortable	16	84.2
	Somewhat Comfortable	2	10.5
Previous Participation in AR Testing	Not Comfortable	1	5.3
	Yes	0	0
	No	19	100

The application's usability was the subject of the second section of the questionnaire. Based on their use of the AR agricultural greenhouse application, participants were asked to rank several aspects. The purpose of the usability questions was to evaluate the application's efficiency and usefulness. Each question was rated using a five-point scale. The questionnaire, consisting of 10 questions from the System Usability Scale (SUS) detailed in Table 7, was administered to the participants. All responses were quantified by assigning numerical values to the Likert scale ratings: 'Strongly Agree' was converted to 5, 'Agree' to 4, 'Neutral' to 3, 'Disagree' to 2, and 'Strongly Disagree' to 1.

4. RESULTS AND ANALYSIS

The results in this section verify the achievement of the research project objective, employing a descriptive methodology through the deployment of the solution on an agricultural greenhouse prototype. The prototype serves as a digital transformation demonstrator space, demonstrating the potential of AR in modernizing agricultural procedures. The implementation of our solution involved the convergence of physical devices with an AR application in an IoT setting. This communication facilitated seamless interaction between the physical sensors installed in the greenhouse and the AR app. Data transmission in real-time was efficiently facilitated, enabling timely monitoring and response to greenhouse environmental fluctuations. This aspect is crucial for precision agriculture since timely data are required for optimal crop development conditions. To ensure the reliability of information transmitted, we have established decimal values on the virtual variables of the Node-RED platform and on HTML scripts used in data processing. This specific setting enabled us to precisely show environmental conditions such as temperature, humidity, and moisture content within the AR application. It is most important that farmers can make effective decisions based on reliable representation of data to real-time conditions.

A key feature of our solution is the accurate superposition of digital data onto the physical environment. This was achieved through advanced AR techniques that align virtual elements with their real-world counterparts. In the context of the agricultural greenhouse, this means that farmers can visualize critical data overlaid directly onto plants and equipment. For instance, temperature readings are displayed above specific sections of the greenhouse, and moisture levels are shown near



Figure 5. Augmented Reality application view showing real-time data visualization with digital twin model.

the soil, providing an intuitive understanding of the spatial distribution of these parameters. The user experience of the AR application was evaluated to ensure it met the practical needs of farmers. Feedback indicated that the application significantly enhanced the ability to monitor and manage the greenhouse environment. The intuitive interface and real-time data overlay reduced the time required for data interpretation and decision-making processes. Additionally, the AR application facilitated remote monitoring, allowing farmers to oversee greenhouse conditions from any location, thus increasing operational efficiency. Figure 5 shows the AR application view displaying real-time data visualization at the entrance to the greenhouse with the digital twin model, which displays various information about the greenhouse.

Table 7. Summary of testers' responses to the AR greenhouse application.

N°	Question	Scale				
		1	2	3	4	5
1	I think I would like to use this system frequently.			1	4	14
2	I found this system unnecessarily complex.	13	2	2	2	
3	I thought this system was easy to use.			2	3	14
4	I think I would need assistance to be able to use this system.	3	13	2	1	
5	I found the various functions in this system were well integrated.			1	5	13
6	I thought there was too much inconsistency in this system.	10	4	3	2	
7	I would imagine that most people would learn to use this system very quickly.			4	6	9
8	I found this system very cumbersome/awkward to use.	11	5	2		1
9	I felt very confident using this system.		4	1	6	8
10	I needed to learn a lot of things before I could get going with this system.	2	11	4	2	

4.1 Usability Testing

The usability of the AR application combined with IoT and Digital Twin technologies for agricultural greenhouse management was assessed using the System Usability Scale (SUS). An organized approach was used to guarantee accurate outcomes. First, all replies were tallied by giving the Likert scale ratings numerical values: 'Highly Agree' was converted to 5, 'Agree' to 4, 'Neutral' to 3, 'Disagree' to 2, and 'Strongly Disagree' to 1. The user demographics and usability evaluation questions made up the two primary components of the questionnaire. The demographics section captured essential information such as gender, age, and prior experience with IT technologies.

This was crucial for understanding the background of the participants and contextualizing their feedback. The usability section assessed the user-friendliness of the prototype. It was required that participants had experience with mobile devices because they had to rate the usability of the application. Because they had used mobile apps before, the participants were able to identify and describe both the advantages and disadvantages of the AR application's usability. The study in question had 19 participants in total, including both male and female users. To compute the final SUS score, the raw scores were first adjusted by subtracting 1 from each score. This adjusted score was then processed using the standard SUS formula to derive the overall usability score, Equation (5)

$$SUS_{\%} = 2.5 \left(20 + \sum (SUS1, SUS3, SUS5, SUS7, SUS9) - \sum (SUS2, SUS4, SUS6, SUS8, SUS10) \right) \quad (5)$$

The comprehensive findings of the participants' usability testing are shown in Figure 6. The information gathered by the SUS offers a perceptive evaluation of the application's efficacy and user satisfaction. Extensive documentation and analysis were conducted on every participant's answer to guarantee precise and dependable usability metrics. The graphic summarizes the entire user experience and identifies important areas that might use development. It shows the strengths and areas that need to be improved in the AR application for managing agricultural greenhouses.

$$Final\ SUS\ Score\ (All\ Participants) = ((82,5 + 85 + 77,5 + 95 + 92,5 + 72,5 + 85 + 95 + 90 + 65 + 77,5 + 95 + 82,5 + 60 + 67,5 + 90 + 67,5 + 80 + 90)/1900) \cdot 100\ \% = 81,58\ \%$$

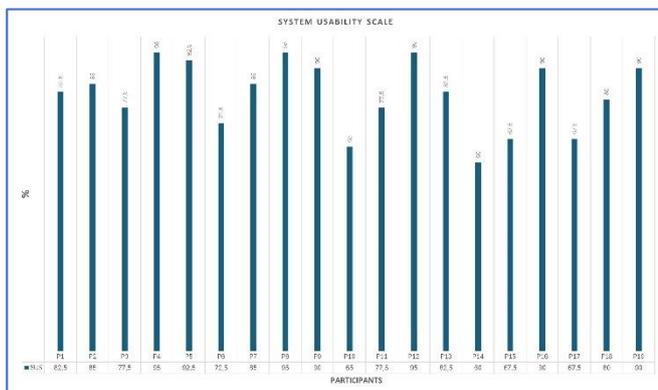


Figure 6. SUS evaluation results for each participant.

Table 8. Interpretation of SUS.

SUS Score	Adjectival Rating	Grade
> 80.3	Excellent	A
68 - 80.3	Good	B
68	Okay	C
51 - 68	Poor	D
< 51	Awful	F

The application performed exceptionally well, as evidenced by the final score of 81.58 % on the System Usability Scale (SUS) grading indication, where a score of more than 80.3 is considered excellent. This high rating suggests that people thought the program was very good and easy to use. The outcomes show that the users engaged with the application's functionalities without difficulty and also liked using it. The favorable comments highlight how well the application works in the intended setting and how much potential it has to improve user experience. The application's excellent usability based on the information presented in Table 8, and user acceptance are further validated by Figure 7, which shows the "grade" SUS acquired by the number of participants.

4.2 System Capabilities

The proposed solution integrates a modular environment with cutting-edge technologies and tools, offering significant benefits to both end-users and agricultural professionals. By enabling comprehensive monitoring and configuration of the system's operation, the AR prototype eliminates the need for costly additional equipment, such as headsets, external modules, cameras, and screens. This reduction in hardware requirements not only lowers costs but also simplifies the user experience, making the technology more accessible. One of the standout advantages of the mobile application is its inherent mobility, allowing users to conduct AR sessions directly within the agricultural greenhouse. This functionality is achieved through meticulous software configuration and methodology, which consider the real-world agro-environmental conditions of greenhouses. The resulting hybrid experience is user-friendly and inclusive, catering to a wide range of users, including the elderly, who may not be familiar with advanced technology.

In addition, the integration of a wearable device for tracking data gives a holistic view of the greenhouse's status. The availability of critical information in real time through the

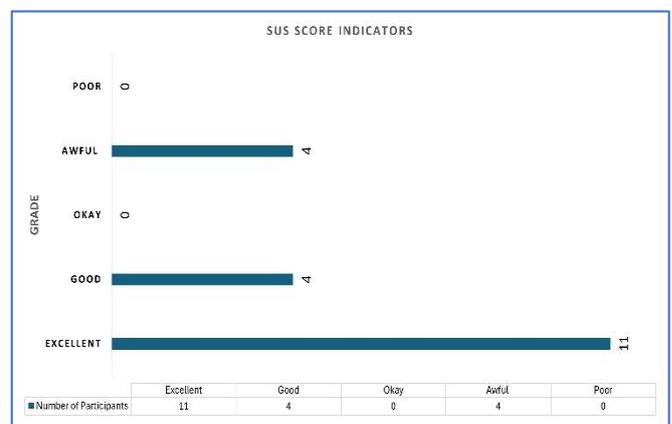


Figure 7. SUS grade distribution among participants.

feature enables agricultural specialists to make more informed decisions. Even though the combination of AR and IoT technologies is not a new strategy, their application in sustainable agricultural prototypes is not quite common. The solution presented herein exploits this synergy for building an off-the-shelf environment for designing AR applications, with IoT sensors incorporated from the initial design stages. The innovative contributions of this work are threefold. Not only are novel combinations of technologies and functionalities in terms of AR and IoT being merged into the system, but a new platform is also being created for development. This development platform allows agricultural specialists to design novel, innovative environments for interacting with and monitoring the status of greenhouses. The analysis of existing literature and comparison of capabilities highlights the novelty of the solution, suggesting it can have a substantial impact on the field of agriculture, particularly in the management of agricultural greenhouses. The proposed system enhances remote monitoring capabilities with active participation from greenhouse operators. This involvement allows for real-time modification of system parameters and the creation of new settings, thus providing a dynamic and responsive approach to greenhouse management. The implementation of the proof-of-concept prototype validates the effective synergy of the technologies used and demonstrates the system's ability to deliver the functionalities using current devices. Figure 8 shows examples of AR application view displaying real-time data visualization inside the agricultural greenhouse.

The augmented reality application shown in Figure 6 illustrates the seamless integration of real-time data visualization and control mechanisms into the greenhouse environment. Thanks to augmented reality, users can interact with essential agricultural parameters intuitively and efficiently. The ability to directly perceive and modify key environmental factors such as CO₂ level, light intensity and soil moisture directly in the AR interface increases the precision and responsiveness of

greenhouse control. Not only is this app more efficient in operation, it also enables proactive decision-making. The instantaneous feedback from the AR system enables growers to tune the growing conditions in real-time, which directly translates into higher crop yield and more efficient use of resources. Historical data trends also allow detailed analysis and adjustment of farming practices to ensure the long-term productivity and sustainability of greenhouse operations. The first graph in Figure 8 represents a plot of CO₂ level in the greenhouse across a specified period, enabling agricultural specialists to monitor CO₂ level fluctuations and make informed adjustments on how to enhance plant development and air quality. The second picture has a dial for adjusting light intensity, with the current reading and a trend graph over time. This enables fine-tuning of light conditions, which is critical for managing plant growth and minimizing energy expenses by using the best lighting timetables. The third picture is of soil moisture control, with real-time readings of current soil humidity and a 24-hour trend graph. It offers the optimum soil conditions, prevents over- or under-watering, and promotes even plant health by virtue of the operators' ability to respond instantly to changes and automatically make irrigation adjustments [27].

4.3 Analysis of Test Reliability

In order to verify the reliability and validity of the data sensed by our IoT sensors and expressed by our augmented reality app, we carried out an extensive reliability test. The test's primary purpose was to gauge how sensor data was accurately represented in the AR interface and how reliable our system was for real-time greenhouse management. The reliability test was conducted for 75 measurements, and each logged data for six significant parameters: indoor temperature, outdoor temperature, indoor humidity, soil moisture, light and CO₂ levels. The sensor values obtained actually were cross-checked

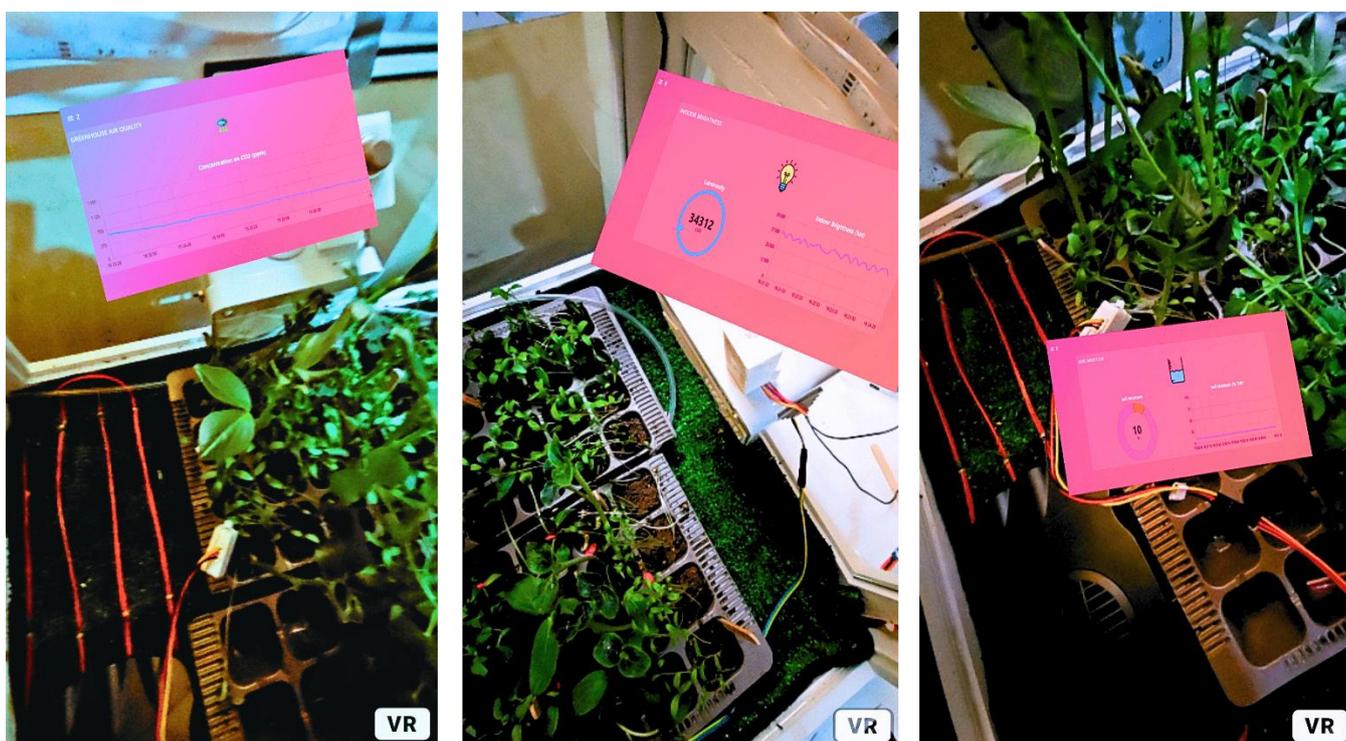


Figure 8. Examples of Augmented Reality application view displaying real-time data visualization inside the agricultural greenhouse.

with the values shown in the AR app to determine the validity of data representation. The performance testing of all the environmental parameters yielded very precise results. With a maximum variance of 0.2°C, the average inaccuracy for indoor temperature was 0.1°C between the actual and displayed readings. In the same manner, the exterior temperature readings showed a maximum variation of 0.2°C and an average inaccuracy of 0.1°C. The system reported an average relative humidity (RH) difference of 0.1%, with a maximum inaccuracy of 0.3% RH, for indoor humidity. The measurements of soil humidity indicated a peak deviation of 0.2% RH and an average error of 0.1% RH. The largest variation in luminosity was 1292 lux, with an average error of 120 lux. Finally, the CO2 levels presented an average error of 1 ppm with a peak deviation of 5 ppm. These results indicate a high degree of reliability and accuracy in the sensors' readings. Figure 9 provides a comparison of the agri-environmental variables of the greenhouse, actual data, and values represented in the AR model.

The results indicate a high level of reliability in data presentation, with minimal errors for all parameters. The consistency of the data representation was confirmed by a low standard deviation, testifying to the ability of the AR application to faithfully reflect real-world conditions. However, the test also highlighted areas for improvement. Despite the overall accuracy, occasional discrepancies were observed, particularly under extreme conditions or rapid changes. These variations underline the need to continue refining sensor calibration and data processing algorithms to further improve accuracy.

4.4 Latency Assessment of the AR and IoT Integrated System

We conducted a thorough latency test to ascertain the effectiveness of our AR app combined with IoT nodes for greenhouse management. Our primary goal was to check the time taken between the gathering of data by the IoT sensors and the display of the information by the AR app. This was carried out to examine the responsiveness and effectiveness of the integrated system. In order to understand and solve latency issues better, we analyzed optimizations at both the computational and communication levels with a specific

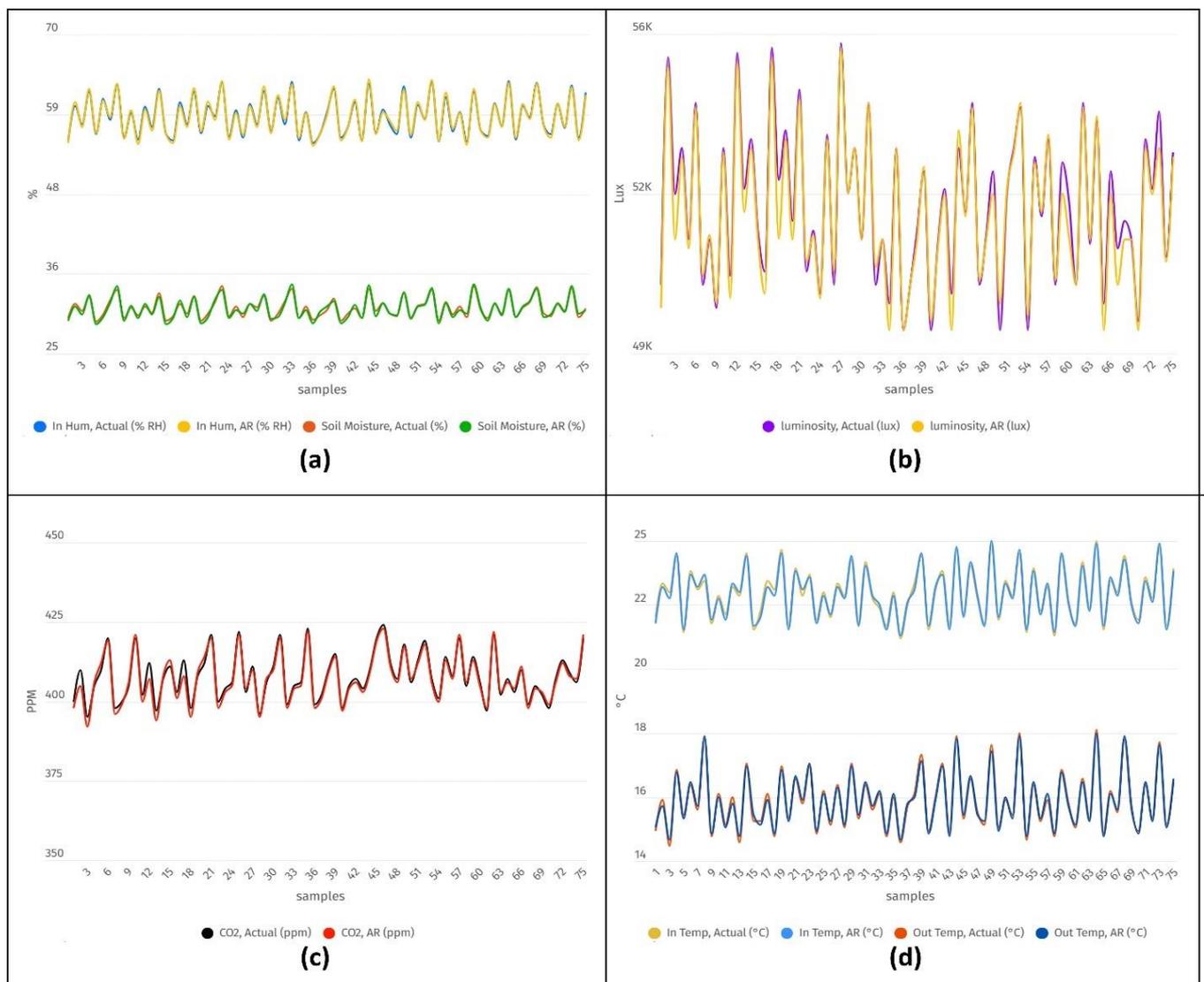


Figure 9. Comparative analysis of greenhouse agri-environmental parameters: actual vs. AR model, (a) indoor humidity and soil moisture: actual vs. AR model, (b) indoor luminosity: actual vs. AR model, (c) indoor CO2 levels: actual vs. AR model, (d) indoor and outdoor temperature: actual vs. AR model.

emphasis on the role contributed by MQTT and edge computing. Computational layer optimizations were achieved through the improvement in local processing efficiency with offloading the lightweight operations, i.e., filtering and threshold detection, into the ESP8266 microcontroller directly. This minimized the redundant or irrelevant data that was required to be transmitted. Besides, we employed a dynamic sampling strategy: in the case of stationary environmental conditions, we reduced the data sampling rate to minimize computation and communication overhead, and in the case of high-speed changes, we increased the sampling frequency to maintain system responsiveness. To encode the data, we employed compact JavaScript Object Notation (JSON) representations and started investigating binary serialization formats, especially in bandwidth-constrained applications or computation-limited devices.

Latency tests were conducted across 20 trials and averaged to obtain average, minimum, and maximum latencies at various phases of data processing. A summary of the detailed latency values for each trial is presented in Table 9. Overall system latency before optimizations was found to be on average 493.5 milliseconds, with a minimum of 455 milliseconds and a maximum of 540 milliseconds, showing inconsistency in system performance. The stability of system responses is described by the standard deviation of 23.4 milliseconds Equation (6), while the results also pointed to bottlenecks for improvement—most significantly, the data processing steps through Node-Red and the AR data rendering pipeline. To reduce delays in communication, we tuned the setup of the MQTT protocol. Following empirical experiments, we settled on Quality of Service (QoS) level 1 as an acceptable balance between latency and reliability of delivery. While QoS 0 provided the lowest latency, it caused message loss occasionally and was therefore a trade-off to system integrity. At the other extreme, QoS 2 imposed significant overhead for little gain in reliability in our application. In addition to QoS tuning, we also switched from an MQTT broker hosted in the cloud to an installed Mosquitto broker on a Raspberry Pi. This change significantly reduced

Table 9. Summary of latency measurements across 20 trials.

Trials	IoT Node-Server (ms)	Server-DT (ms)	DT-AR (ms)	Total Latency (ms)
1	120	150	200	470
2	115	155	210	480
3	130	160	205	495
4	125	145	190	460
5	140	170	220	530
6	110	140	205	455
7	125	155	215	495
8	135	165	225	525
9	120	150	200	470
10	130	160	210	500
11	140	170	230	540
12	115	145	205	465
13	125	155	220	500
14	130	160	210	500
15	140	165	215	520
16	110	150	200	460
17	125	160	225	510
18	135	170	220	525
19	120	155	210	485
20	125	150	205	480

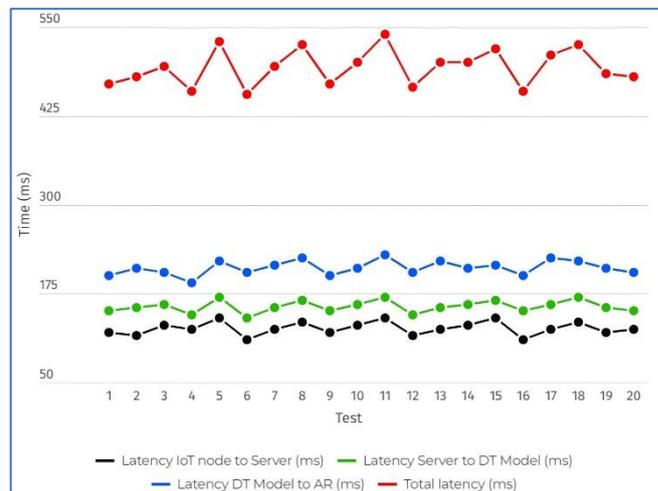


Figure 10. Latency test results.

round-trip transmission latencies, resulting in an enormous improvement in responsiveness. Other optimizations involved minimizing the subject hierarchy to limit parsing latency and combining several sensor values into single-packet messages, which lowered message frequency and network traffic

$$\sigma = \sqrt{\frac{\sum(\text{Total Latency} - \text{Average Latency})^2}{\text{Number of Tests}}} \quad (6)$$

These enhancements were manifested in later latency tests. Average overall latency was reduced from 493.5 milliseconds to around 280 milliseconds for the same test setup. This increase validates the utility of the presented methods in minimizing end-to-end delay and boosting the responsiveness of the system by a considerable proportion. These findings are essential in facilitating real-time performance in actual greenhouse management scenarios, where the fast visualization of environmental parameters is important for prompt decision-making. Figure 10 presents an example of the latency test results for 20 samples. The graph is a visual representation of the latency measurements and reports the range of latencies observed in trials, along with the average, minimum, and maximum values.

5. DISCUSSION

Our research shows that integrating AR and IoT technology into agricultural greenhouse management is a major step forward for precision agriculture. The ramifications of our findings, their fit with our study goals, and their wider significance in the scientific community are explored in this discussion section.

Our main goal was to validate an AR-based solution that synchronizes IoT and digital twin technologies for improved agricultural greenhouse management. The result confirms that our solution was able to achieve this successfully. Physical sensors incorporated into the AR application facilitated the easy transmission of real-time data, allowing timely monitoring and reaction to environmental changes - a highly crucial aspect in optimizing the conditions for crop growth. The high fidelity of data representation, achieved through precise configuration of decimal values on the Node-RED platform and HTML scripts, captures the essence of precision in precision agriculture [28]. This is in agreement with existing literature that emphasizes the

importance of precise real-time data for effective agricultural management. The System Usability Scale score of 81.58% captures that our AR application is not only usable but also easy to use. Volunteers noted that intuitive UI and data overlay in real time reduced time needed for data interpretation and decision-making processes considerably. This conforms with earlier work concerning the relevance of user-oriented design in AR to agriculture (Anastasiou et al., 2023). The ability for remote tracking of greenhouse conditions also encourages operational effectiveness, a role that has increasingly been found to be the essential factor in current farming systems (Boursianis et al., 2020). Latency testing was utilized to calculate an average response time of 493.5 milliseconds, and that is satisfactory for applications in real-time. However, the result also set performance variation, with maximum latency at a maximum of 540 milliseconds. This difference would have an impact on the system performance, particularly when there are rapid environmental changes in high speeds. Optimization methods, including computational offloading and dynamic data sampling, have been incorporated to reduce such latency, and further enhancements on these are recommended to enhance the system performance [29].

Our advanced AR techniques allowed for the accurate superposition of digital data onto the physical environment, providing farmers with an intuitive understanding of spatial distribution parameters. This feature is crucial for precision agriculture, allowing farmers to visualize critical data directly overlaid onto plants and equipment. Previous studies have shown that such visualization capabilities can significantly improve decision-making in agriculture. Our approach further validates these findings by demonstrating practical implementation in a greenhouse setting. Usability testing confirmed the robustness of our AR application. With minimal errors in sensor data representation, the system proved to be both accurate and reliable [30]-[31]. However, occasional discrepancies under extreme conditions highlight the need for ongoing refinement of sensor calibration and data processing algorithms. These findings align with those of other researchers who have observed similar challenges and emphasized the importance of continuous improvement in sensor technology for agricultural applications. Our solution's modular environment, which reduces hardware requirements and simplifies the user experience, offers significant benefits. The application's mobility allows for AR sessions directly within the greenhouse, making it accessible to a wide range of users, including those unfamiliar with advanced technology. The integration of wearable devices for real-time monitoring further enhances decision-making capabilities. While the average latency of 493.5 milliseconds is acceptable, there is room for improvement to ensure real-time performance, particularly during data processing phases.

The combination of AR, IoT, and digital twin technologies suggested here has in-built support for advanced resource optimization. Monitoring and visualization of environmental parameters in real time enable condition-based control over irrigation, lighting, and ventilation systems, with significant savings on energy or water consumption that is avoidable. As opposed to conventional installations, our solution allows instant, data-based interventions with reduced waste and greater operational precision. Moreover, the digital twin feature allows users to simulate various scenarios and predict system behavior before making physical changes, resulting in improved resource planning. The AR interface also proves to be useful in that it

simplifies the interpretation of complex information and enables faster decision-making, thus facilitating shorter periods for suboptimal environmental conditions that are likely to result in wasteful use of resources. These shared traits are well within the principles of sustainable agriculture and are highly suited for optimizing energy and input utilization under greenhouse conditions [32]. Quantification of the benefits using empirical data and long-term implementation will be the subject of subsequent work.

While our study has successfully demonstrated the feasibility and benefits of integrating AR and IoT, combined with a digital twin technology in agricultural greenhouses, several areas warrant further exploration. Enhancing sensor accuracy under extreme conditions and rapid changes is critical for improving system reliability. Future research could also explore the integration of more advanced AR techniques and machine learning algorithms to provide predictive insights into greenhouse management. Expanding the application to diverse crop types and greenhouse environments would further validate its versatility and scalability [33].

6. CONCLUSIONS

To meet the technical demands of the agricultural greenhouse industry, this study investigates the integration of IoT, DT, and AR technologies. The potential of these cutting-edge technologies to enhance the productivity and control of agricultural operations was demonstrated by the development of a prototype system. Through an augmented reality application, the system allows for real-time monitoring and viewing of sensor data from physical Internet of Things devices, facilitating user engagement and control. The MQTT protocol is used to transmit data, guaranteeing effective and safe communication. The successful implementation of the prototype system highlights the capability of AR to provide real-time insights and control, enhancing the usability and efficiency of greenhouse management. Despite some challenges with marker detection, the AR interface generation was effective, validating the system's practical application. To further improve system intelligence and user experience, future work will concentrate on integrating AI-based algorithms and utilizing the spatial awareness capabilities of cutting-edge gadgets. Our research opens the door to more intelligent and productive farming methods by proving the viability and efficacy of utilizing IoT, DT, and AR technologies in agricultural settings. By providing a scalable solution that can be tailored to different agricultural situations, this study advances the industry's technical frontier and adds to the larger area of digital transformation in agriculture.

AUTHORS' CONTRIBUTION

Hicham Slimani: Funding acquisition, Writing – original draft, Investigation, Methodology, Software, Formal analysis, Data curation.

Jamal El Mhamdi: Project administration, Investigation, Writing - review & editing, Supervision, Formal analysis, Validation.

Abdelilah Jilbab: Conceptualization, Supervision, Investigation, Project administration, Writing - review & Editing, Formal analysis, Validation.

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