Towards an Integrated IoT and AI Architecture for Sustainable Agriculture: The Case of Oman

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Abstract— Emerging Technologies in Smart Farming: Emerging technologies, such as the Internet of Things (IoT), Artificial Intelligence (AI), robotics, and big data, offer positive advancements in enhancing productivity, sustainability, and resilience in farming. The purpose of this document is to give analyses and syntheses of 47-plus studies that are academic, industry, and government with a focus on the dry and resource-thin territories. Using the towns of Oman as a case study, the author identifies several principal issues, including insufficient water, soil salinity, technology fragmentation, and a lack of cybersecurity. The interrelation of AI for automation and other technologies as adjuncts for precision irrigation and sensors within a collaborative environment is further emphasized. The author suggests several data gaps on system interoperability, a digital divide, the system-agnostic behaviors of the farmers, and other issues. The findings of this research document contribute toward extensional transitions of the 5th industrial technology in farming. It deviates attention from siloed technologies to a holistic approach in ecosystems and provides a scaffolding basis for other smart farming in resource-thin circumscriptions.

Keywords— *Smart Farming, IoT in Agriculture, AI, Sustainable Agriculture, Precision Irrigation, Cybersecurity, Thematic Analysis*

INTRODUCTION

The integration of the Internet of Things (IoT), Artificial Intelligence (AI), robotics, and data analytics into agriculture as smart farming or precision agriculture allows further advancements in the productivity, efficiency, and sustainability of crops and livestock and the sustainability and efficiency of the agriculture sector as a whole. These innovations are having a particularly great impact within the sector in developing regions of the world and areas with the most environmental and socio-economic constraints. The technological smart farming infrastructure in a region should not only be available but also be contextually relevant to the locality's agroecological and infrastructural conditions. Oman's use case exemplifies the contextual applications of smart agriculture. The country has moist monsoon-fed coastal zones and dry inland areas, providing great opportunities for testing precision farming technologies. A variety of commercial and academic initiatives aim to investigate the diverse regions' smart agriculture potential. Jinan Tech Greenhouse and Al Najd Agricultural City are nearby local agroecological zones incorporating AI and IoT systems. The Wadi Dawkah Smart Forest project is also an example of digital farming in the context of heritage farming.

In the Dhofar region, the recently recognized UNESCO World Heritage Site of Wadi Dawkah contains more than five thousand frankincense trees (Boswellia sacra) and, in 2022, became the first smart forest in the GCC as a result of a collaboration between Amouage and the Ministry of Heritage and Tourism of Oman. Recently developed technologies that utilize remote geotagging and the internet of things (IoT) enabled the first smart irrigation system capable of remote monitoring and diagnostics of a tree's sustainability, resin yield, and health. Oman, having coupled the southern region's Salalah hydroponic farm, as well as the new high-altitude Jabal Akhdar (Alila), which, in July 2024, was the first to achieve soilless black heirloom tomato production in the region, is targeting the complex of systems agriculture to enhance food security, conserve water, and support agritourism. Along the same lines, the Rahab Farm in Shalim, built by Nakheel Oman Development Company, is a showcase of carbon-neutral agriculture achieved with the cultivation of 6 km² of date palms using precision irrigation. In collaboration with Sultan Qaboos University, the Ministry of Energy and Minerals is leading the Jinan Tech Project, which focuses on IoT and Controlled Environment Agriculture (CEA) systems.

The first phase of the project involves developing climate-smart greenhouses expected to serve 200 active participants, including the farmer, SMEs, and pupils. The Computer Vision and Machine-Learning-Based Disease Detection System developed by the University of Technology and Applied Sciences (UTAS) further improves Proactive Crop Management [1]. The AI-based tools provide an active pest management system and autonomous drone monitoring, enhancing the Agri 5 Vision's objectives of economically sustainable farming and the use of automated pest sprayers. Other innovations include IoT-assisted urban farming, designed for indoor gardening and optimizing the limited space available in apartments. Resource (pest, irrigation) management efforts are being enhanced by structured datasets from ICARDS and IDFIP [1] [2]. This paper presents a smart farming case study, challenges, and innovations from Oman. It outlines the contextual background of the region and the foundational technologies, main activities, and completed implementation initiatives to draw broader conclusions. The literature review captures the technologies and practices of smart agriculture, while in the methodology, the author employs thematic analysis of more than twenty pertinent publications. The research on smart agriculture key themes includes the integration of water, efficiency, smart infrastructure, and policy. The findings are organized according to the OECD Framework for the Governance of EPS.

The global and regional positioning advocates for the construction of a singular, AI-based system designed to tackle local intricacies. Although the pilot projects exist, there is still a lack of investigation of smart farming systems across diverse agro-ecological regions. Recent studies focusing on a singular technology have largely dominated the landscape, and there seems to be little to no consideration of their interaction, scalability, or sustainability. A framework that combines regional focus, predictive analytics, and automated systems is overdue. The authors of smart farming technology applied in a structured and united approach can alleviate the environmental constraints and exponentially increase the food supply, 4 predict the potential. This paper is meant to address the author's goal of improving the "smart" in sustainable smart farms through technological innovation; thus, the structure of the document serves this objective. The introduction includes the rationale and the background; the technology and the regions of innovation are the foci of the literature review; the methodology section presents the thematic analysis of the principal case studies; the findings survey the operational constraints and the most impactful practices and policies; and the discussion presents the most effective integrated AI systems the author suggests are the focus of implementation.

The paper ends with concluding remarks that encapsulate my primary arguments and present suggestions for continued research and policy development.

Related Work

The advancement of smart farming has been internationally documented. In particular, there is the inexpensive moisture sensor irrigation control system from AlSarmi and Al-Riyami that uses Arduino moisture sensors to facilitate irrigation of small urban farms. Likewise, there is other research that focuses on a Bluetooth-controlled robotic arm with six degrees of freedom that was designed with SolidWorks and is 3D printed. The arm is servo-operated and uses Arduino to convert mobile slider input commands to servo movements, thereby demonstrating low-cost robotics for the automation of agriculture in Oman. On top of the hardware innovations, the use of AI in agriculture has also been growing. Rajesh et al. has developed a machine learning crop monitoring system that integrates image recognition with a Raspberry Pi and historical datasets from ICARDS and IDFIP to forecast crop yield under various environmental conditions. Another similar work has also developed an Arduino soil monitoring system that tracks the moisture and temperature of the soil and streams the data to Microsoft Power BI for irrigation visualization and more effective real-time irrigation. In a more global context, the authors of the document performed practical work outside of the country to demonstrate the SWAMP system for precision irrigation. All of these works confirmed the smart irrigation technologies can be adapted and scaled to different ecosystems and socio-economic conditions.

The implications of smart agriculture for food security and economic diversification have drawn the attention of several other scholars studying Oman's smart agriculture ecosystem. One study, for example, focusing on the potential of certain vegetables that are considered staple foods and cash crops, underscored the dual purpose of vegetables produced. A study examined the efficiency of production with data obtained from a survey involving 118 farms and concluded that the adoption of modern practices would result in an increase of more than 20% in the level of production. [6]. Additional information from neighboring countries is also valuable. One study conducted in Jordan analyzed the impact of the COVID-19 crisis and rapid urbanization on food, water, and energy systems and the resultant pressures. With more than half of households in the study reducing the intake of meals, it proposed the need for resilient urban redevelopment to ensure food security in the long term. The Smart Vertical Farming Hub at Isra University also supports the idea of climate-resilient urban agriculture, growing crops like leafy greens and strawberries in controlled, indoor environments [7]. The Hub is also the initiator of a carbon-neutral project, where the planting of 30,000 lemon trees is expected to increase the production of lemons in the region by 38% in 2023. The project provides both economical benefits and environmental preservation through the use of smart irrigation and groundwater sensors. The transformation, however, depends on the participation of the private sector.

Sustained partnerships among academia, governmental bodies, and industry actors are required to facilitate knowledge transfer and attain long-term sustainability. Omani academic institutions remain instrumental in the development and ongoing research in smart agriculture. These research activities and collaborations across several sectors demonstrate the value of nimble policy frameworks, in conjunction with local research, to adapt and apply global innovations to the case of sustainable smart farming in Oman and other countries with similarly restrictive farming systems. Methodology The thematic analysis of 77 publications over the period of 2012–2024 serves as a basis to apply a qualitative review methodology. The publications were selected through established criteria based on their relevance to smart farming technologies and the geography of Oman. A coding scheme was applied to retrieve information to build on the five principal themes. The outcome of the analysis is presented in Table 1.

Table 1 shows thematic analysis results.

Theme	Description	Example Projects	Key Insights

Water Efficiency	Precision irrigation and water use	Rahab Farm, SWAMP, Hydroponics Salalah	Saves water, boosts yield in arid regions
Smart Infrastructure	IoT, AI, robotics, automation	Jinan Tech, UTAS detection, Arduino sensors	Enables real-time monitoring and automation
Policy Integration	Alignment with Vision 2040	Al Najd City, Jinan Tech	Government support drives adoption
Academic Innovation	Research and prototypes	SQU, UTAS projects, Arduino arm	Advances tailored tech and builds skills
Cross-Sector Partnerships	Collaboration across sectors	Wadi Dawkah, Rahab Farm, Alila Jabal Akhdar	

SMART AGRICULTURE FRAMEWORK

This smart farming framework has been developed based on the previous literature and the current scholarly publications on digital agriculture systems. It demonstrates the crucial elements that academics consider essential in the realization of smart agriculture, such as IoT sensors, artificial intelligence, cloud computing, and decision support systems. These elements are explained in the literature as the technological advancements needed in order to resolve the issues of agriculture, such as the environmental pressures, resource wastage, automation, and the growing demand for resource use. This framework integrates these technologies into a single model meant for real-time tracking and monitoring, predictive decision-making, and overall systems optimization in accordance with the literature, both theoretical and applied in the field.

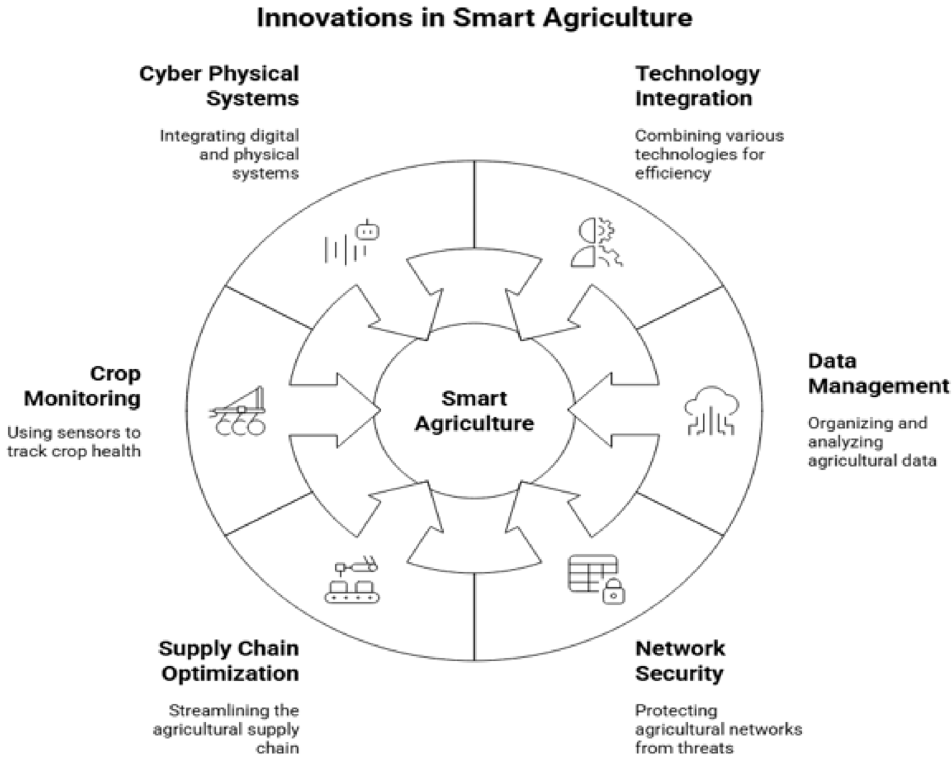

Figure 1 shows the suggested smart agriculture framework.

CHALLENGES IN SMART AGRICULTURE

The Challenges Facing Smart Agriculture in Oman The most prominent obstacles facing smart agriculture in Oman come from a triad of formations, including the technological, environmental, and socio-economic factors ([8]). Examples of the environmental obstacles include the phenomenon of soil salinization, increased temperatures, and overpopulation suffering from high productivity demands on Oman's limited freshwater resources ([8][9][5]). Effective mitigation of these issues requires the deployment of technologies such as artificial intelligence, the Internet of Things, and systems based on machine learning, which facilitate the tasks of monitoring crops, resource management, and pollution management ([7][4][9][10]). Moreover, productivity is also increased in the crop yield through smart management systems based on IoT and sensor systems tailored toward the effective management of crop productivity and resource systems ([5]). The existence of a wide range of issues is a challenge for smart agriculture in Oman and also the biggest barrier to the adoption of such technologies.

Oman also lacks agricultural technologies, funding, and local farming expertise. These issues can be tackled through supported policy advocacy for smart, sustainable agricultural policy frameworks that diversify Oman's sustainable agricultural focus. Oman needs to integrate its agricultural technologies. The adoption of new technologies in agriculture in Oman is strategically important and also highly challenging. The adoption of farming technologies, such as drones, IoT sensors, and other forms of agriculture, can make agriculture in Oman more sustainable and productive. However, the routine upkeep and implementation of these technologies can be expensive. Oman's agriculture can also benefit from technological advancements in AI, robotics, and remote IoT for higher efficiency and lower labor utilization. Given Oman's soil and water challenges, high soil and water salinization, and extreme temperatures, the adoption of smart solar-powered greenhouses that automate irrigation, venting, and lighting is warranted with the potential for water and energy conservation. Even in Oman, remote-controlled automated farming systems use IoT applications that require little to no human interaction.

Nonetheless, there are additional factors, like traditional networking constraints, that challenge the development of multi-tiered long-range wireless network (LoRaWAN) routers and satellite communication architectures, which are more sophisticated and costlier [5]. Ultimately, improved sustained investment in advanced sustainable agritech would accrue from the successful mitigation of cost and connectivity issues.

This section discusses the management challenges in smart agriculture in Oman. The use of IoT and sensor technology enables the collection of extensive datasets, which are difficult to integrate, manage, and use [15]. The collection of such data is referred to as high volume, velocity, and variety and requires sophisticated systems for management [16][17]. The lack of common standard protocols also complicates these challenges and severely reduces the level of device, software platform, and service interoperability, which in turn limits the effectiveness of smart farming solutions [18]. Other more general frameworks, such as Smart Farming Oriented Big-Data Architecture (SFOBA), which includes IoT, big data, and automated systems, have been devised to streamline the processing of agricultural data [15]. In addition, certain focus-reference frameworks for smart farming data systems have also been devised from domain analysis and architectural modeling [16]. While these are real advances, they do nothing to mitigate the scarcity of scientific literature about data management for smart agriculture.

Purposeful research is justifiable to fill the gap for usage of IoT application security for digital agriculture cybersecurity. Digital Transformation Cybersecurity Challenges Framework Integration of Farming Systems Technologies Networks Cyber Security Challenges the Privacy Security Dual Focus System Integrated Smart Agriculture. Security challenges of diverse agricultural practices, development of advanced cyber blockchain technologies, and horizontal geospatial security integrated technologies are still in the development phase. [21][19] Protection of infrastructures from hostile cybersecurity threats has resulted in elevating cyber defense challenges integrated into IoT systems for agriculture [22]. [23] Other comprehensive literature reviews have provided active cyber breach monitoring, reviewed response frameworks for breach, and security posturing of the systems [10]. Concerning the Application of Networks and Sensors in Precision Farming, it emphasizes the gap in precision agriculture and integrated cyber security systems.

Supply Chain Optimization in Smart Agriculture Solidifies Defining and Optimizing the Agricultural Supply Chain in Oman.

Considering Oman's agricultural sector, smart farming technologies span all parts of the agricultural value chain. The aim of these technologies, via the Internet of Things, sensors, and data analytics, is improving the efficiency of the operation, lowering the cost of production, and increasing output [10][25]. The use of the IoT applications in farming systems in the agricultural supply chain has the ability to increase the quality of the agricultural products and enhance effective cost reduction [26][27]. More importantly, IoT devices strengthen the productivity of the supply chain via systems for environmental monitoring and irrigation control and greenhouse automation [10]. Moreover, the use of IoT concepts in supply chain controls improves operational clarity, cost reduction, and responsiveness, as well as demand-driven agility in the market [28]. Evidently, such technologies lead to a more effective and efficient supply chain system [26]. However, the supply chain still requires some ethical, social, and environmental considerations in the use of these technologies [10]. There is also the issue of technological inexperience and entrepreneurial reluctance on the part of smallholder farmers [26][27]. Nonetheless, the innovative employment of IoT and big data in the agricultural supply chain has the potential to significantly enhance the efficiency of management and reduce unpredictability, in addition to increasing transparency [29]. Oman still has to integrate modern technologies and traditional farming methods to have the full advantage of what is available and close the gaps outlined in [10]. Crop Monitoring in Smart Agriculture Crop Monitoring in Smart Agriculture Oman's smart agriculture vision focuses on productivity and efficiency in resource utilization through the implementation of advanced technology.

IoT sensors are useful in smart farming IoT ecosystems because they supply soil water parameters, moisture, and environmental conditions in real-time. This technology focuses on increasing productivity and efficiency in resource utilization through remote crop monitoring and other smart farming techniques. Improvements in crop yield are achieved by the real-time control of irrigation and other environmental conditions. These technologies aid the agricultural process management. However, these technologies make it possible for precision agriculture to meet given standards and efficiently manage the estimation, organization, and supply of the entire system. Given these innovations, a pertinent issue is the fusion of modern smart farming with conventional practice. This fusion has considerable ethical, social, and ecological challenges. Cyber-Physical Systems in Smart Agriculture The Role of Cyber-Physical Systems within Smart Agriculture. Smart agriculture relies on cyber-physical systems because they enable the integration of the digital and physical components of farming activities. CPS enables the incorporation of IoT sensors for the real-time collection, processing, and communication of data related to the ongoing monitoring and management of key agricultural variables, including soil and atmospheric conditions. [34][35][36][37]. Smart agricultural IoT systems include advanced communication systems, usually cloud-based, that offer complete functionality for data processing and comprehensive data integration [34][38]. These systems are being advanced to cyber-physical agricultural systems (CPAS) with the adoption of precision sustainable agriculture and improvement of operational efficiencies [35]. The integration of these systems gives rise to different issues, such as the absence of seamless privacy and the demands for suitable supervision, as the digital intrusion countermeasures afforded to these vulnerable systems present the dangers of submitted unlawful access to security of access-controlled crime [39]. The absence of emphasis on the Oman context brings to the forefront the under-researched potential that CPS could offer agriculture. Machine Learning Applications in Smart Agriculture In Oman, the use of Machine Learning (ML) and Artificial Intelligence (AI) technologies is transforming agrarian practices to be more efficient, sustainable, and profitable.

AI and ML technologies enable more efficient irrigation and more advanced, tailored management of crops and pests using predictive technologies [41][5]. Furthermore, the remote sensing and advanced neural networks technology underpins the sustainable, precise agricultural decision-making and optimal performance of complex farming operations [41][42][43]. Given Oman's challenges in farming, the precision technologies of AI and ML will greatly assist in the promotion of sustainable agriculture and food security [6][5]. AI technologies also add economic value by improving precision in the monetized agronomic operations of planting, fertilizing, irrigating, and harvesting, thereby increasing profitability [40]. Furthermore, in Oman, for the advancement of agriculture, AI/ML technologies yield predictive enhancement and the management of soil, pests, and diseases, thereby fostering innovation [44]. These innovations align with Oman Vision 2040 and assist Oman in Table 2 shows smart agriculture framework details.

Table 2 Smart agriculture framework details

Challenge Area	Description	Identified Needs	Influencing Factors	Solutions	References
Environmental and Socio-Economic Barriers	Soil salinity, water scarcity, extreme heat, limited tech access	Identifies core barriers to smart farming adoption	Harsh climate, lack of infrastructure and training	Context-specific strategies and capacity building	[7][4][8][9][5][10][11]
Technology Integration and Security Issues	High costs, limited connectivity, cyber risks	Highlights need for secure, cost-effective systems	Technological complexity, data vulnerability	Low-cost platforms, cybersecurity frameworks	[12][13][3][5][14][22][23][24]
Efficiency and Sustainability Enhancement	Real-time crop monitoring, supply chain optimization	Improves resource use and farm productivity	Yield variability, inefficient input management	Precision farming and automation tools	[10][25][26][27][28][29]
Cyber-Physical System Integration	Cloud-linked sensors for automated farming control	Enables responsive, real-time interventions	Delayed operations, manual dependency	Sensor-based automation and control systems	[34][35][36][37][38][39]
IoT, AI/ML, Sensors, and Robotics	AI for predictions; IoT for precision irrigation	Supports data-driven, optimized resource use	Data overload, poor monitoring accuracy	AI-augmented analytics and precision systems	[7][40][41][42][43][44][45][46][47]
Agricultural Cybersecurity Solutions	Blockchain and secure authentication models	Protects data and system integrity	Risk of cyberattacks and data breaches	Robust cybersecurity protocols	[19][20][21][22][23][24]

Proposed Smart Agriculture Architecture and Specifications

In order to bring the conceptual framework to life, the current work advances a multi-tiered Smart Agriculture Architecture incorporating the elements of sensing, communication, analytics, and applications into one system. First, environmental and agronomic data is obtained from a range of perception technologies at the bottom layer, such as IoT sensors monitoring soil moisture, pH, electrical conductivity, CO_2, temperature, and humidity, which are augmented with drone multispectral imaging as well to assess the field from above. Data is then sent to the Network Layer based on Oman's geographical communication infrastructure—Low Power Wide Area Network (LoRaWAN) gateways for long-range, low-power, 5G for high-bandwidth, and satellite IoT for remote rural areas. In the cloud/edge layer of the system, real-time agricultural intelligence is obtained where edge devices perform essential preprocessing tasks for the cloud's machine learning models focused on irrigation, disease, and yield. The machine learning models depend on irrigation control, disease identification, and yield estimation. In the top layer of the system, the Application Layer, farmers, agronomists, and policymakers can interact with the system data via web dashboards and mobile applications that illustrate key agronomic factors like NDVI, evapotranspiration, and energy–water efficiency ratios and offer automated on-off control and alerts for irrigation.

This architecture integrates differing areas, including conceptual modeling and practical field implementation, enabling scaling and transferring anywhere, including Oman and other arid and semi-arid geographies within the GCC.

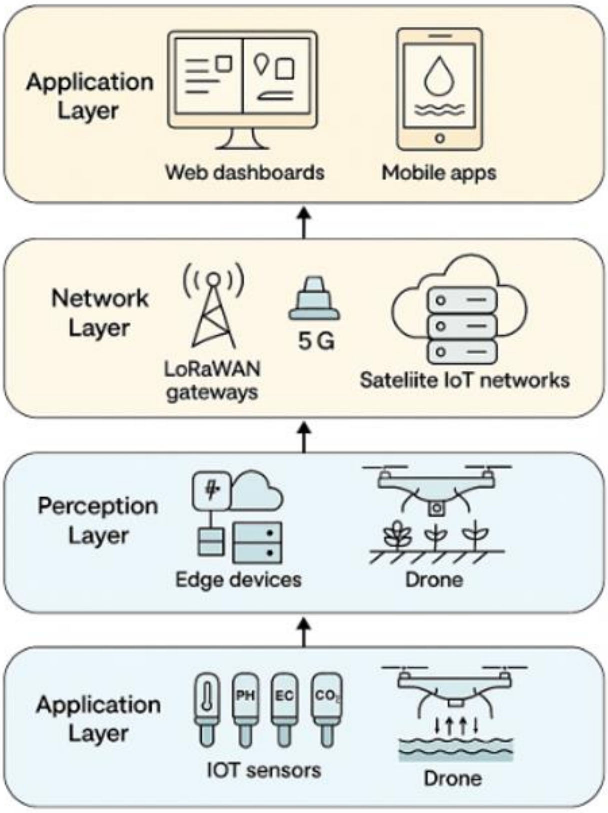

Figure 1. Smart agriculture architecture

Discussion

The thematic analysis of this study continues in the same direction as the literature review, where global research shows that the IoT, AI, robotics, and cyber-physical systems offer the greatest value when integrated systems are developed as opposed to having these technologies function in silos. The literature on smart irrigation, cyber-physical systems in agriculture, and AI-based crop monitoring has consistently highlighted that the siloing of technologies has resulted in the inability to achieve efficiency and/or scalability in value retention in arid regions of developing economies; this has also been highlighted in the literature [3], [5], [7], [14], [34]. In this work, Omani case studies, especially Rahab Farm, Wadi Dawkah, and the Jinan Tech projects, have also shown that the value of water use efficiency, system responsiveness, and predictive accuracy are enhanced when the IoT and edge–cloud integrated computing and automated irrigation systems are designed and deployed within an integrated framework. The literature reflects on the environmental constraints of water, heat, and salinity and these environmental constraints, which have also been largely reflected in the Omani context.

There have been many studies that have shown how sensitive arid-zone farming is to climate variability and water scarcity. This analysis has shown how these changes have shaped tech adaptation in Oman and reinforces findings in other countries, which show smart farming in arid regions requires adaptations to local ecosystems. For instance, the reliance on precision irrigation systems found in several studies is also observed in the large-scale water-efficient date-palm farming at Rahab Farm, while the use of controlled-environment agriculture at Jinan Tech is consistent with the literature that supports the use of intelligent greenhouse systems for hot climates. A common theme in the literature revolves around data governance and interoperability, with many studies discussing the challenges in managing the high volume, high velocity, and multiple format data streams that agriculture generates. The case studies covering Oman certainly support this, as local projects have been able to implement IoT sensors and monitoring systems but have also continued to encounter challenges surrounding data heterogeneity, system interoperability, and real-time data processing. The challenges surrounding the need for structured data flows, calibrated sensors, and a unified data governance framework have been mentioned in other studies and are also relevant to the Omani deployments assessed in this study.

This alignment further emphasizes the importance of the suggested IoT–AI architecture incorporating edge analytics, cloud computing, and standardized communication protocols. Cybersecurity is the most urgent issue pertaining to smart agriculture systems globally, as documented within the literature. Location and authentication research, secure device authentication, and intrusion detection systems, alongside trust models that use blockchain, indicate that the agricultural IoT data networks have vulnerabilities to data leaks, spoofing, and unauthorized access. Numerous research documents [19], [20], [21], [22], [23], [24] illustrate the IoT security vulnerabilities within Oman's agricultural systems, leading to the conclusion that security maturity is still inadequate and that sensor and device deployment outstrips the available security measures. This outcome corroborates the literature on different security tiers and explains the significant enhancement of cybersecurity features within the architecture. It also identifies the socio-economic adoption barriers in the reviewed literature, namely the high cost of deployment, low levels of training, and limited digital skills in smallholder farmers [25], [26], [27], [28]. This is evident in Oman, where the lack of funding, coupled with the agricultural systems' technical complexity and skills shortage, continues to hamper the exploitation of the available promising prototypes.

There is a resemblance between these barriers and the ones faced in the similar regions, particularly Jordan, India, and Sub-Saharan Africa, where researchers have pointed out the relation between the confidence and digital literacy of farmers and the effectiveness of smart farming [7], [10], [12]. The comparison of the international studies reviewed with the results obtained in Oman shows that the same primary conditions must be met: interdependent infrastructural systems, self-sustaining secure data ecosystems, communication networks of the system, and people-oriented social engineering. The integrated IoT-AI architecture proposed in this paper is, hence, not just a reaction to local deficiencies but a synthesis of empirical evidence and of the best practices and of the challenges that remain to be addressed as documented in the global literature [2], [3], [5], [15], [19], [25], [34].

CONCLUSION

The results obtained in this study substantiate and corroborate the patterns and findings presented in the literature review that confirmed the findings in literature that smart agriculture technologies—particularly IoT systems and AI-driven analytics—combined with cyber-physical ecosystems and robotics attain the highest levels of performance and the highest degree of effectiveness from their utilization and deployment in an integrated and interoperable cyber-physical ecosystem as opposed to in silos. The literature review noted the persistent and intractable issues within arid and resource-constrained agriculture, namely, the fragmentation of data flows, limited water availability, high soil salinity, inadequate cybersecurity, and the high cost and technical complexity of the systems. The thematic analysis of Omani case studies in this paper demonstrates how Oman's data and GIS infrastructure and resource management systems reflect the growing and documented global studies in arid climates. Advanced irrigation, sensor-based resource monitoring, AI in resource management, and low-power IoT in integrated resource management systems provide measurable efficiencies and productivity gains in agriculture. Projects such as Rahab Farm, Jinan Tech, and the Wadi Dawkah Smart Forest reflect practical examples of the technological categories analyzed in the literature review. Predictive analytics, integrated CPS, IoT in large volumes, and adaptive greenhouse automation are examples of automation in the agritech sector.

The literature identifies gaps regarding data governance, interoperability, cybersecurity preparedness, and user readiness, which also appear to be present in the pilot deployments in Oman. Drawing on the findings from 47 academic and industry research papers, the paper affirms the need for ecosystem-level frameworks that integrate systems for standardized data management, resilient communication, multi-level stakeholder governance, and validated AI. These needs reflect the gaps identified in the literature and comply with the framework architecture presented in this paper. The international case studies reviewed, particularly SWAMP and SFOBA, illustrate that Oman is yet to develop the conditions to support hybrid scalable smart farming. The findings also support the literature review's thesis: for smart agriculture to be really sustainable, the focus must move from the technologies themselves to systems that are coordinated, interoperable, secure, and flexible. The prospects for smart farming in Oman are clear, but the transition to Agriculture 5.0 will require long-term field validation, inclusive capacity building, data governance, and policy-innovation alignment. These will close the gaps identified in the literature and place Oman as a potential scalable model for other semi-arid and arid regions focused on the transformed technologically enabled agriculture.

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Authors' Contributions

Abdulaziz Aborujilah: writing, evaluation.
Samir Hammami. Editing and proofreading.
Nasser Tabook: forming and publication.

Conflict of Interest

The authors declare that there is no conflict of interest.

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