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TESIS DOCTORAL

IoT-Based Agricultural Innovations: Cost-Effective Platforms for Smallholder Farmers in Nepal and Lower- and Middle- Income Countries

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Ritu Raj LAMSAL

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El alumno del Programa de Doctorado en Ingeniería de Telecomunicación, Ritu Raj Lamsal, con pasaporte nº NPL 08388979, es primer autor de los siguientes artículos publicados en revistas indexadas en los *Journal Citation Reports* (JCR) de la *Web of Science* (WoS):

- Ritu Raj Lamsal, P. Karthikeyan, P. Otero y A. Ariza. "Design and implementation of internet of things (IoT) platform targeted for smallholder farmers: from Nepal perspective." *Agriculture* 2023, 13, 1900, 28 septiembre 2023. DOI: 10.3390/agriculture13101900.
- Ritu Raj Lamsal, U.K. Acharya, P. Karthikeyan, P. Otero y A. Ariza. “Implementing internet of things for real time monitoring and regulation in off-season grafting and post-harvest storage in citrus cultivation: a case study from the hilly regions of Nepal ". *Agriengineering* 2024, 6(3), 2082-2100, 8 julio 2024. DOI: 0.3390/agriengineering6030122.

Además, el candidato es primer autor del siguiente artículo:

- Ritu Raj Lamsal, Mamta Bhattarai, Umesh Acharya and Pablo Otero. “Monitoring and regulating climatic condition of polyhouse for successful off-season grafting of citrus fruits using internet of things platform". *International Journal of Agriculture, Environment and Biotechnology*, Vol. 15 (Special Issue): 417-422, August 2022. DOI: 10.30954/0974-1712.03.2022.17.

Los dos primeros artículos publicados avalan su tesis doctoral y ninguna otra tesis.

Por todo ello, su tutor académico, Pablo Otero, y los directores de su tesis doctoral, Pablo Otero y Francisco Coslado Aristizábal, autorizan al Sr. Ritu Raj Lamsal a depositar su tesis doctoral ante las Autoridades académicas de la Universidad de Málaga.

En Málaga, a 17 de julio de 2024.

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Abstract

This thesis investigates the design and implementation of a low-cost, reliable IoT platform tailored for smallholder farmers, with a particular emphasis on lower- and middle-income countries such as Nepal. The majority of farmers in Nepal belong to smallholder farming communities, working on small plots of land and often relying on traditional farming methods and family labor. These methods have become less efficient in today's agricultural landscape, highlighting the need for affordable and accessible IoT-based systems to enhance agricultural productivity. The problem analysis identifies the inefficiencies of traditional farming practices and the lack of suitable IoT solutions for smallholder farmers. A comprehensive review of the state of the art in IoT applications for agriculture reveals a gap in cost-effective, scalable, and reliable solutions designed specifically for smallholders. This thesis proposes a novel IoT platform that is cost-effective, customizable, scalable, and reliable, addressing the unique challenges faced by smallholder farmers. The proposed IoT platform enables farmers to monitor and control real-time sensor data related to their crops, livestock, and other agricultural assets using web and mobile-based applications. It integrates various sensors, microcontrollers, and communication modules to collect and transmit data to a cloud server. This data provides valuable insights that assist farmers in making informed decisions regarding irrigation, ventilation, and other environmental controls. Figures of merit for the platform include affordability, ease of use, scalability, and reliability. The platform's design ensures it can be widely adopted by smallholder farmers with limited financial resources. Comparative analysis with existing solutions demonstrates the proposed platform's superior cost-effectiveness and suitability for smallholder contexts.

Experimental assessment involved deploying the IoT platform in polyhouses for off-season grafting of citrus fruits and in cold chambers for post-harvest storage. These case studies demonstrated that the platform could maintain optimal climatic conditions, extending the grafting period and improving crop yields. The platform also aided in post-harvest storage by remotely monitoring and regulating temperature, humidity, and gas content to preserve fruit freshness and extend shelf life. The empirical results of this research indicate that the IoT platform not only enhances efficiency in crop cultivation but also provides a scalable solution applicable to other agricultural settings. The successful implementation of this platform highlights the potential of IoT technologies to transform traditional farming practices for smallholder farmers. Overall, this study emphasizes the importance of localizing IoT solutions for smallholder farmers by involving them in the development process and encouraging the adoption of the technology. This participatory approach ensures the technology meets the specific needs of the farmers and fosters a sense of ownership. This research serves as a model for future initiatives to integrate technology into agriculture, consequently improving food security and livelihoods of the farmers.

Summary

IoT-Based Agricultural Innovations: Cost-Effective Platforms for Smallholder Farmers in Nepal and Lower- and Middle- Income Countries

The integration of IoT technology has immense potential to transform agriculture sector especially in the agriculturally based countries like Nepal. By bridging the gap between traditional farming practices and modern technology, IoT in agriculture can significantly empower farmers, enhance food security, and contribute to global sustainability goals. Investments and adoption of modern technology like IoT in agriculture helps to build a more resilient, efficient, and sustainable agricultural sector for the future. The challenges in addressing food security for a growing population, projected to reach 9.7 billion by 2050, emphasizes the critical role of agriculture in sustaining livelihoods and economies worldwide.

The agriculture sector is vital to Nepal's economy. It contributes significantly to GDP and employs a large portion of the population, particularly through smallholder farming. The agriculture sector contributes to around one-third of the nation's GDP and provides employment to two-thirds of the population. However, its contribution to the overall GDP has declined over time. Agriculture contributed 36.64% of the GDP, which then decreased to 23% by 2022. Several factors have led to this decline, including smallholder farmers leaving land uncultivated due to low profitability, lack of modernization and technology, and reliance on traditional farming approaches. Additionally, many youths have sought foreign employment to sustain their livelihoods due to low profits in agriculture. Nepal has diverse geoclimatic conditions. Smallholder farmers manage small plots of land across different climatic zones. These zones range from subtropical plains to alpine regions. The farmers grow a variety of crops. This geographical diversity helps build resilience against climatic uncertainties. It also highlights the importance of agro-biodiversity for maintaining agricultural productivity and food security. However, smallholder farmers in Nepal face numerous challenges that threaten their livelihoods and hinder agricultural productivity. Limited access to modern technology, unpredictable weather patterns, and inefficient traditional farming practices are primary concerns. These factors contribute to uncertainty in agricultural productivity, economic instability, and significant pre- and post-harvest losses. Such challenges exacerbate rural poverty and often lead to youth outmigration in search of better economic opportunities, leaving agricultural communities with labor shortages and demographic shifts.

In response to these challenges, there is an urgent need for innovative, affordable solutions to enhance the productivity and sustainability of smallholder farming. The IoT emerges as a promising technological solution that bridges the gap between traditional agricultural practices and modern technology. IoT technology allows farmers to monitor crucial parameters such as soil moisture, temperature, and crop health in real-time. This data-driven approach empowers farmers to make informed decisions regarding irrigation, fertilizer application, pest management, and other agricultural practices. Such precision farming techniques not only optimize resource use but also help mitigate risks associated with climate variability and

environmental factors. Moreover, IoT facilitates improved market access through traceability systems and real-time market information. These innovations enable farmers to connect directly with markets, improve supply chain efficiency, and negotiate better prices for their produce. For smallholder farmers who often struggle with market integration and face challenges in accessing timely market information, IoT can significantly enhance profitability and empower decision-making.

To effectively design and implement IoT systems for smallholder and precision farming in Nepal, several key factors have been identified in this study . First and foremost is cost-effectiveness: the system should be affordable for smallholder farmers, incorporating low-cost sensors and scalable cloud infrastructure. This ensures accessibility for farmers with limited financial resources. Reliability is another critical factor. Given the challenges with electricity and internet connectivity in rural areas, the IoT system must be robust enough to handle intermittent conditions. This includes designing systems that can operate efficiently despite power outages or limited network availability. User-friendliness is essential for the widespread adoption of IoT systems specially for small holder farmers. The system should have a simple user interface, requiring minimal technical knowledge to operate. This makes the technology accessible to a broad range of users, including those with limited experience with digital tools. Customization is crucial to address the diverse needs of different crops and livestock. IoT systems should be adaptable, ensuring broad applicability across various agricultural contexts. This allows farmers to tailor the technology to their specific requirements, enhancing its effectiveness. Data security is paramount for gaining the trust of farmers. Ensuring the security and privacy of collected data protects sensitive information and builds confidence in the system.

The proposed IoT platform for smallholder farmers presents compelling real-world applications across various agricultural scenarios. Some of these applications include:

Polyhouse Tunnel Agriculture: The adoption of polyhouse tunnels for crop cultivation is on the rise. Within these controlled environments, the IoT platform offers effective management of climatic conditions and irrigation, ultimately leading to increased productivity and higher profits for farmers. Nursery Operations (Fruit and Flower Plants): Grafting fruit and flower plants in a nursery demands meticulous internal microclimate control. The IoT platform provides an ideal solution for managing these conditions, ensuring optimal growth and development of plants. Additionally, off season grafting can be conducted to extend the grafting period to meet the demand of thee grafted saplings. Mushroom Farming: Mushroom cultivation is a popular among smallholder farmers in Nepal due to its quick turnaround and profitability. The IoT platform can play a pivotal role in mushroom farming by enabling precise control of environmental factors such as temperature, and humidity and light intensity which are critical for successful mushroom growth. Poultry Farming: A significant number of smallholder farmers in Nepal operate small-scale poultry farms. The IoT platform facilitates real-time remote monitoring of crucial parameters within the poultry farm, including temperature, humidity, and air quality. It can also be employed to automate feed and water systems. Additionally, real-time heating, cooling, and lighting systems can be automated to optimize energy consumption. Farm Security and Access

Control: Ensuring security and controlled access to a farmer’s premises is of great importance. The IoT platform can be utilized for this purpose. Integrating sensors and actuators such as motion sensors and alarms provide early intrusion detection and safeguard the farm.

The key contributions of this study involve designing a customized IoT platform for smallholder farmers in Nepal, focusing on a low-cost, localized, reliable, and community-sharing approach. The platform is developed to support both web and mobile applications. To validate the reliability and robustness of the platform, field experiments on different agriculture-related sensor data were carried out over a significant period. This study also includes a case study by deploying the IoT platform in real-world scenarios for off-season grafting of citrus fruits and post-harvest storage. The outcomes of the methodology and approach were as expected and met the research objectives.

The research lays the foundation for future studies focused on innovating and refining IoT-based agricultural systems for smallholder and community farmers in developing countries like Nepal. Opportunities include further development of the IoT platform, exploration of new applications, and integration with emerging technologies like artificial intelligence, Bigdata and blockchain. Future studies conducted over a longer period can evaluate how IoT interventions impact smallholder farmers' livelihoods, resilience, and sustainability. Understanding how technology is adopted and its socio-economic effects within farming communities will be a key focus. Additionally, comparing different regions or countries can provide insights into the factors that influence the adoption of IoT in agriculture. This comparison can help in scaling successful interventions and identifying best practices. Overall, the thesis aims to contribute comprehensive insights and practical solutions to enhance agricultural productivity, sustainability, and socio-economic development in Nepal's smallholder farming communities through IoT technology.

This thesis is structured into five chapters. It begins with an introductory chapter that addresses the challenges prevalent in Nepalese agriculture, particularly among smallholder farmers. It articulates the need for tailored IoT solutions to address these challenges and establishes the research's significance. Introductory chapter outlines the objectives, motivation, scope, and organization of the study, providing a roadmap for the subsequent chapters. The second chapter highlights the literature review and background that examines existing research on IoT applications in agriculture, both globally and within Nepal. It explores the unique characteristics of smallholder farming in Nepal and evaluates the efficacy of current IoT solutions. It also discusses the challenges and opportunities in adopting IoT technologies in Nepalese agriculture. Chapter 3 describes the design and implementation of IoT system platform and its features. It elaborates on the conceptualization of the IoT system architecture and the implementation. It covers the hardware setup, software development, testing procedures. Further it also provides the possible inclusion of the platform in real world use case scenario. Chapter 4 focuses on Case Studies and Field Trials, examines the IoT system's performance in real-world agricultural conditions. It discusses the selection of pilot sites, data collection methods, user feedback, and evaluation of the system's impact on farming practices. Through case studies and field trials in offseason grafting and pre- and post-harvest storage of citrus fruits , the study offers empirical evidence of the system's effectiveness and potential benefits.

Finally, Chapter 5 serves as a conclusion and offers insights into future directions. It summarizes the key findings and contributions of the research. It concludes by reaffirming the research's significance in advancing agricultural development in Nepal and underscores the importance of continued innovation and collaboration in harnessing the potential of IoT technology for the benefit of smallholder farmers.

This section of the thesis deals with the relevant literature review and necessary background for conducting the research. The major highlight is focused on various aspects on Internet of Things. Beginning with the fundamental of Internet of things, sensors and devices, IoT layer architecture , Various IoT protocols and connectivity , it also highlights about the major fields of application of IoT. Additionally, it also covers the cloud based IoT model and service providers. Subsequently the concentration of this section is on IoT and its adoption in agriculture. It also briefly summaries the domain of IoT in agriculture like Precision agriculture, Smart farming, Digital farming, Farm automation, Connected agriculture IoT (AIoT), Sensor-based agriculture, Remote sensing in agriculture etc.

The integration of IoT technology into agriculture, known as IoT-based agricultural operations, is revolutionizing farming practices worldwide. This transformation is driven by the need to increase agricultural productivity, optimize resource use, and mitigate environmental impact in the face of global challenges such as population growth, climate change, and food security. IoT architectures in agriculture typically involve networks of sensors and actuators deployed across farms to monitor and manage various aspects of crop growth, soil conditions, environmental parameters and livestock health. These sensors collect real-time data on soil moisture, temperature, humidity, and crop health, which is transmitted to centralized systems or cloud-based servers and platforms for analysis. Fog or Edge computing plays a crucial role by processing data closer to where it's generated, reducing latency and enabling quicker decision-making.

Precision agriculture is a cornerstone application of IoT in farming, enabling farmers to tailor their practices based on precise data insights. By using IoT sensors to monitor and analyze field conditions, farmers can optimize irrigation schedules, apply fertilizers and pesticides more efficiently, and predict crop diseases. This targeted approach not only improves crop yield and quality but also minimizes input wastage and environmental impact. Smart farming takes precision agriculture a step further by integrating IoT with artificial intelligence (AI) and data analytics. AI algorithms analyze large volumes of IoT-generated data to provide predictive insights and recommendations for optimizing farming operations. For example, predictive models can forecast crop yields based on weather patterns and recommend optimal planting times and harvest schedules.

The IoT protocols and standards ensure seamless communication between devices and systems. Widely used Protocols includes HTTP/HTTPS, MQTT, CoAP, Zigbee, BLE, LoRaWAN and 6LoWPAN.The choice among them depends on specific requirements such as power consumption, communication range, scalability, and security. State of the art description of these protocols are summarized in the thesis.

IoT connectivity options include wired and wireless solutions. Wired connectivity uses physical cables like Ethernet and serial connections (RS-232/RS-485), offering high reliability and data rates. These are suited for stable environments but less flexible for mobile use. Wireless options vary: Wi-Fi provides high data rates locally but limited range and interference issues; Bluetooth supports short-range communication for wearables; Cellular networks (3G/4G/5G) offer broad coverage for remote or mobile IoT devices. Low-Power Wide-Area Networks (LPWANs) like LoRa, Sigfox, and NB-IoT cater to long-range, low-power needs in applications such as smart agriculture, ensuring connectivity over vast distances with minimal energy consumption.

IoT platforms are essential for managing connected devices, processing data, and developing applications within the IoT ecosystem. They are crucial for scaling IoT projects across various industries, facilitating innovation and driving digital transformation. In agriculture, IoT cloud platforms like AWS IoT and Azure IoT Hub offer extensive integrations within their ecosystems, providing flexibility and scalability. Platforms such as ThingSpeak emphasize data visualization and are suitable for smaller-scale agricultural projects. These platforms enable device management, data collection, and analytics, with varying levels of industry-specific capabilities. Advanced features in platforms like Azure farm beat, Google Cloud IoT and IBM Watson IoT include AI and machine learning, enhancing data-driven insights for agricultural applications. Overall, cloud-based IoT platforms play a pivotal role in modern agriculture by enabling seamless connectivity, monitoring, and analysis of IoT device data.

Several case studies highlight the practical applications and benefits of IoT in agriculture. For instance, IoT-enabled precision agriculture has been successfully deployed in vineyards to monitor soil moisture and temperature, leading to improved irrigation efficiency and grape production. In livestock farming, IoT-based monitoring systems track animal health and behavior in real-time, enhancing breeding management and milk production. Drones equipped with IoT sensors and cameras are used in crop health monitoring to detect pest infestations and nutrient deficiencies early, enabling timely interventions and higher yields.

Challenges remain in the widespread adoption of IoT in agriculture, including the initial costs of IoT infrastructure, connectivity issues in rural areas, and concerns about data privacy and security. Addressing these challenges requires investments in infrastructure development, policy support, and farmer education. Improving internet connectivity and access to affordable IoT technologies are critical steps towards enabling smallholder farmers to benefit from IoT innovations.

The proposed IoT architecture for smallholder agriculture represents a significant advancement in integrating technology to enhance farming practices. It incorporates a robust system of sensor networks, edge computing capabilities, and cloud infrastructure tailored specifically for smallholder farmers. Designed to be affordable and user-friendly, the architecture empowers farmers with limited resources to access and benefit from advanced technological solutions. This scalability ensures that the system can adapt to the evolving needs of farmers, providing flexibility in selecting application services that best suit their specific requirements.

Figure 1 shows the customized IoT platform approach. It highlights how the platform is adaptable and customizable. Users can adjust the system to meet their specific needs. This flexibility applies to both sensor and switch services. Farmers can deploy sensors to monitor environmental conditions or use switches to control irrigation systems and climate settings in greenhouses. The platform allows farmers to configure it based on their operational preferences.

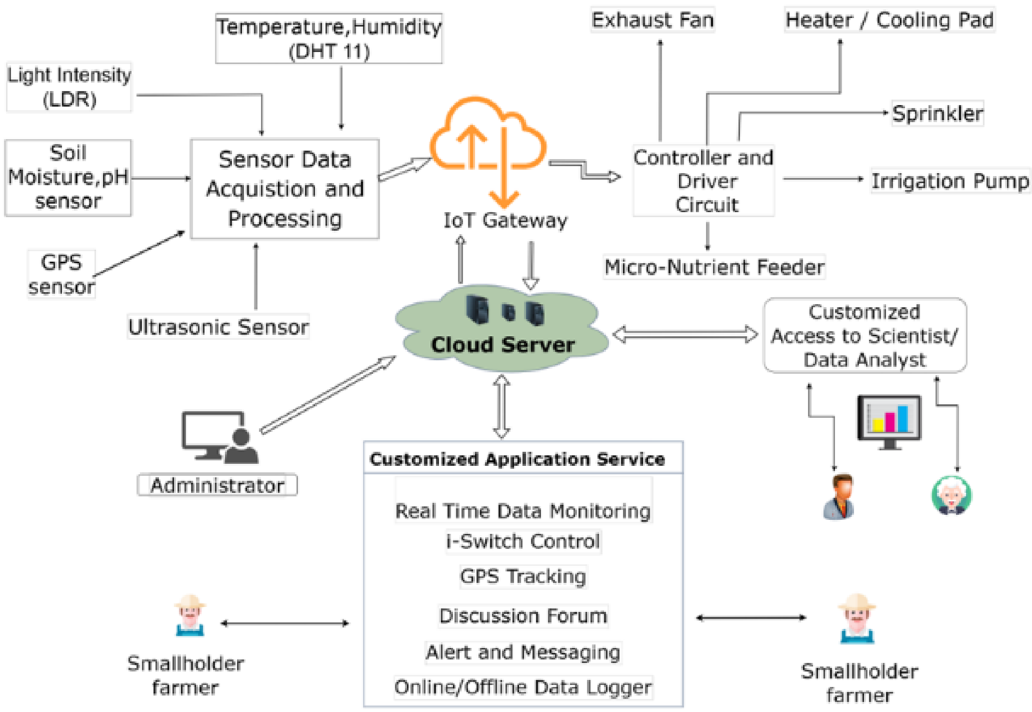

Figure 1 Customized IoT Platform

Central to the proposed architecture is the user-centric application and service structure, which facilitates role-based access and seamless device deployment. Administrators play a crucial role in creating distinct user roles, encompassing farmers, custom users, scientists, and data analysts. End users are equipped with the tools to set up IoT devices in their fields and manage data collected from various sensors. This data, including crucial parameters like temperature, humidity, soil moisture, and pH levels, is meticulously collected, processed, and transmitted to cloud servers for secure storage and analysis.

Key features within the proposed system enhance agricultural operations significantly. Real-time data monitoring and visualization empower farmers to make informed decisions promptly. Through applications like "i-Switch," farmers can remotely control devices critical to their operations, ensuring precise regulation of microclimates essential for optimal crop growth. GPS tracking enables real-time monitoring of agricultural assets, enhancing logistical efficiency and asset management. Alerts and messaging systems notify users of critical events, helping them respond promptly to changes in their agricultural environment.

Data logging and analytics form a cornerstone of the system, providing farmers with comprehensive insights into their farming practices. The architecture supports both onsite and online data logging, ensuring data availability even in areas with unreliable internet connectivity. This hybrid approach combines local storage with cloud-based solutions, enabling continuous data collection and analysis. The integration of a dedicated discussion forum further enriches the user experience, fostering knowledge exchange among farmers, researchers, and experts.

The hardware and application design components of the proposed system are chosen to maximize functionality and efficiency. Microcontroller units like the NodeMCU ESP8266 with Wi-Fi connectivity are used for cost-effective and reliable data transmission. Sensors and actuators collect and control environmental parameters, supporting precision agriculture tailored to local farming conditions. Data is managed on Microsoft Azure cloud services, ensuring scalability, security, and accessibility. This setup caters to diverse user preferences and works across web and mobile platforms.

Performance testing and comparative analysis is carried out to show the robustness and cost-effectiveness of the proposed IoT platform. Server load tests confirm the system's reliability under different user loads. Comparative studies with other existing IoT platforms highlights the cost effectiveness and usability of the proposed IoT system. This makes it accessible to smallholder farmers who want to optimize their agricultural operations using IoT technology. Real-world implementations, such as monitoring and regulating microclimates inside polyhouses validate the practical benefits of the IoT platform. The implementation and results showed that the proposed IoT architecture is reliable and effective in providing smallholder farmers with real-time data and control to improve the efficiency and productivity of their agricultural operations. However, there are also challenges to its implementation, such as the willingness of the smallholder farmers to adopt the technology, community training and support, and further reduction in cost and technical capacity for proper operation.

The software architecture of the proposed IoT system ensures efficient device management, security, and real-time communication. The API facilitates authentication, authorization, and data exchange through REST API endpoints. User authentication uses UserID, password, and client ID, while role-based authorization regulates access. The front end, built with ASP.NET MVC, includes a dynamic dashboard for real-time data visualization and SignalR for real-time communication. The mobile app, developed with Flutter, offers a seamless experience on

Android, allowing users to visualize data and control settings remotely. Data is stored in a SQL Server database, and the entire system is hosted on Microsoft Azure, ensuring high availability, scalability, and disaster recovery. The architecture dynamically adjusts resources to handle varying workloads efficiently.

The thesis follows a case study with the deployment of the proposed system in polyhouse grafting and cold chamber for post-harvest storage in the hilly regions of Nepal. Citrus fruit cultivation, especially mandarin oranges, is crucial to the economy of Nepal's hilly regions due to their ideal geoclimatic conditions. Despite its economic importance, the sector faces several challenges, such as inadequate grafting techniques, low-quality saplings, and ineffective post-harvest storage. The study carried out in this thesis explores these issues and proposes innovative solutions using the proposed IoTtechnology. To address these challenges, we identify key areas for improvement. First, we focus on extending grafting practices during the off-season to ensure a higher success rate and better-quality saplings. Second, we examine different post-harvest storage methods to determine their effectiveness in terms of shelf life, decay loss, and quality of fruit. In addition to exploring post-harvest strategies, this study provides preharvest recommendations for farmers, emphasizing methods to enhance fruit quality and longevity through effective pre-storage practices. **Figure 2** shows Our IoT-based approach for off-season grafting in poly-houses and advanced monitoring for post-harvest storage.

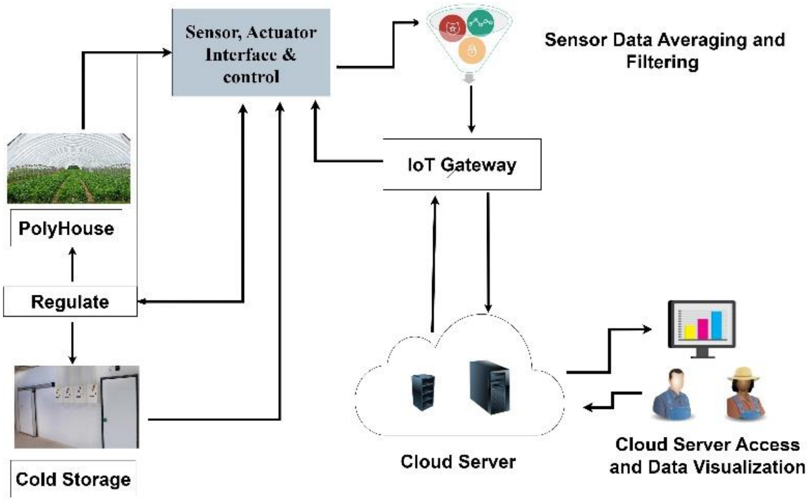

Figure 2 IoT System for Poly house and cold storage monitoring and control

The implementation of IoT technology in off-season grafting is relatively new and innovative concept in context of Nepal. Traditionally constrained by seasonal weather conditions, citrus grafting can now occur year-round within polyhouses equipped with IoT devices. These devices monitor critical parameters like temperature, humidity, and light levels, creating optimal conditions for successful grafting even when external weather is unfavorable. This precise environmental control reduces risks associated with poor graft union and enhances survival rates of grafted plants.

Central to the study is the selection of appropriate grafting methods and scion-rootstock combinations tailored to local conditions. Veneer grafting with trifoliate rootstock has proven highly successful for acid lime and mandarin orange varieties in Nepal's hilly regions. Grafting success rates of 91% for acid lime and 92% for local mandarin orange varieties was achieved. This methodological approach not only extends the grafting season but also ensures higher-quality saplings, addressing a longstanding challenge in the citrus farming community.

Beyond grafting, the study emphasizes optimizing post-harvest management practices, particularly for mandarin oranges. IoT technology with Real-time monitoring within cold chambers enables precise environmental control and immediate responses to deviations, ensuring optimal storage conditions and minimizing post-harvest losses. This integration not only improves storage efficiency but also enhances the economic viability of citrus farming by reducing wastage and extending the market availability of high-quality produce.

Pre-harvest recommendations include surface washing with clean water to remove contaminants and treating fruits with a calcium chloride solution to improve texture and durability during storage. Application of citrus wax provides a protective layer, crucial for maintaining freshness and preventing moisture loss—a critical step often overlooked by farmers but essential for preserving fruit quality. Additionally, our research compared different post-harvest storage methods for mandarin oranges, including room, cellar, and cold chamber. We assessed these methods based on shelf life, Physiological Weight Loss (PWL), and the total soluble solids (TSS) to titratable acidity (TA) ratio. The cold chamber proved to be the most effective method, offering superior conditions for storing mandarin oranges for longer duration. The IoT-based monitoring system played a crucial role in maintaining optimal temperature, humidity, and gas content within the cold chamber, resulting in reduced post-harvest losses and extended shelf life. These findings highlight the transformative potential of IoT technology in mandarin orange cultivation and post-harvest storage.

Despite its transformative potential, the study acknowledges limitations. It was conducted within Nepal's specific hilly regions, where geoclimatic conditions may differ from other citrus-growing regions globally, limiting the generalizability of findings. Moreover, while IoT technology offers significant benefits, initial implementation costs and the need for technical expertise may pose challenges, particularly for small-scale farmers with limited resources. By integrating IoT solutions in both off-season grafting and post-harvest storage stages, farmers can enhance productivity, improve product quality, and uplift their livelihoods. The study provides practical insights and recommendations for optimizing agricultural practices, emphasizing the role of technology in fostering sustainable growth and resilience in the citrus sector. Future research should focus on expanding IoT applications to monitor and optimize other aspects of citrus farming, ensuring continued innovation and advancement in agricultural practices.

This thesis explores the transformative potential of IoT in agriculture, focusing on the unique challenges and needs of smallholder farmers in Nepal. The country's agricultural landscape is diverse, encompassing various climatic zones and contributing significantly to the livelihoods of a large portion of the population. Developing an IoT platform tailored for Nepalese smallholder farmers involves addressing several critical parameters such as cost-effectiveness, reliability, scalability, customization, and ease of use. These factors are essential to ensure that the technology is accessible and beneficial to farmers who have limited financial resources and varying levels of technological literacy.

The thesis identifies significant challenges in developing IoT systems for agriculture, particularly in low and middle-income countries like Nepal. Infrastructure limitations, such as unreliable internet connectivity and power supply, pose significant hurdles. Additionally, the lack of technical skills among farmers, high initial setup costs, and the complexity of managing large volumes of data are substantial barriers. Despite these challenges, IoT technology holds immense promise for enhancing agricultural productivity, resource efficiency, and climate resilience. It can provide real-time data that enables farmers to make informed decisions, optimize resource use, and improve crop yields, thereby increasing their overall productivity and profitability.

A comprehensive literature review was conducted to understand the current state of IoT in agriculture, identify existing gaps, and highlight areas for innovation. This review informed the development of a proposed IoT system specifically designed for smallholder farmers in Nepal. The system architecture is both cost-effective and customizable, utilizing low-cost microcontroller units like the NodeMCU ESP8266 with Wi-Fi connectivity to ensure affordability and reliable data transmission. The software architecture ensures secure and efficient data management, with a user-friendly interface accessible via web and mobile platforms.

Performance testing and comparative analysis with other IoT platforms such as Blynk and ThingSpeak demonstrated the proposed system's reliability and competitive advantages. Server load tests confirmed the system's robustness under varying user loads, and cost analysis underscored its affordability. The system's effectiveness was further validated through a real-world case study conducted in a polyhouse for off-season grafting of citrus fruits. This study demonstrated significant improvements in monitoring and regulating environmental conditions, resulting in a higher grafting success rate and improved crop health. Additionally, the IoT system was used for pre and post-harvest storage of mandarin oranges, showing substantial benefits in maintaining optimal storage conditions, reducing spoilage, and extending the shelf life of the produce.

The results of these studies highlight the practical applicability and benefits of the proposed IoT system. By providing real-time data on critical environmental parameters such as temperature, humidity, and gas content, the system enables farmers to make timely and informed decisions. This leads to optimized resource use, increased productivity, and improved market access for smallholder farmers. The affordability and scalability of the system make it accessible to a wide range of users, ensuring that even those with limited resources can benefit from advanced technological solutions.

In conclusion, this thesis underscores the significant potential of IoT technology in transforming agriculture for smallholder farmers in Nepal. By addressing the specific needs and challenges of these farmers, the proposed IoT system offers a scalable, customizable, and cost-effective solution that enhances productivity, resource efficiency, and climate resilience. The successful deployment of the system for off-season grafting and storage of mandarin oranges demonstrates its practical applicability and effectiveness. As Nepal continues to modernize its agricultural practices, IoT technology will play a crucial role in advancing agricultural development, improving livelihoods, and contributing to the sustainable development of the agricultural sector. This research highlights the importance of continued innovation and collaboration in harnessing the potential of IoT technology for the benefit of smallholder farmers in Nepal.

Recommendations for Future Research: Future research can build on this thesis by exploring several important areas. Long-term studies should be conducted to assess the sustained impact of IoT on farmers' livelihoods and resilience. Research should focus on making IoT systems more scalable and adaptable to different crops and conditions. Integrating IoT with technologies like AI, blockchain, and drones can open new possibilities. Cost-reduction strategies are crucial to make IoT accessible to smallholder farmers, including exploring subsidies and shared community models. Examining policy and regulatory frameworks can support IoT adoption while ensuring data privacy and security. Training programs for farmers should be developed to enhance their understanding and use of IoT. Assessing the environmental impact of IoT technology is important for sustainable development. Comparative studies across regions and countries can identify best practices and adaptable models. Engaging farming communities in the research process ensures relevant and effective solutions. Finally, advanced data management and cybersecurity measures are essential for protecting sensitive information and ensuring data integrity. By addressing these areas, future research can further enhance the potential of IoT technology in agriculture, benefiting smallholder farmers in Nepal and beyond.

Resumen

RESUMEN DE LA TESIS EN ESPAÑOL

Título de la tesis doctoral en español:

Innovaciones agrícolas basadas en IoT: Plataformas rentables para pequeños agricultores de Nepal y de países de ingresos bajos y medios

Presentación

La integración de la tecnología de Internet de las cosas (IoT) tiene un inmenso potencial para transformar el sector agrícola, especialmente en los países basados en la agricultura como Nepal. Al cerrar la brecha entre las prácticas agrícolas tradicionales y la tecnología moderna, el IoT en la agricultura puede empoderar significativamente a los agricultores, mejorar la seguridad alimentaria y contribuir a los objetivos de sostenibilidad global. Las inversiones y la adopción de tecnologías modernas como el IoT en la agricultura ayudan a construir un sector agrícola más resistente, eficiente y sostenible para el futuro. Los desafíos para abordar la seguridad alimentaria de una población en crecimiento, que se prevé que alcance los 9.700 millones de personas alrededor del año 2.050, ponen de relieve el papel fundamental de la agricultura en el mantenimiento de los medios de vida y las economías en todo el mundo.

El sector agrícola es vital para la economía de Nepal. Contribuye significativamente al PIB y emplea a una gran parte de la población, en particular a través de la agricultura a pequeña escala. El sector agrícola contribuye a alrededor de un tercio del PIB de la nación y proporciona empleo a dos tercios de la población. Sin embargo, su contribución al PIB total ha disminuido con el tiempo. La agricultura aportó el 36,64% del PIB, que luego disminuyó al 23% en 2.022. Varios factores han llevado a esta disminución, entre ellos los pequeños agricultores que dejan tierras sin cultivar debido a la baja rentabilidad, la falta de modernización y tecnología, y la dependencia de los enfoques agrícolas tradicionales. Además, muchos jóvenes han buscado empleo en el extranjero para mantener sus medios de vida debido a los bajos beneficios de la agricultura. Nepal tiene diversas condiciones geoclimáticas. Los pequeños agricultores gestionan pequeñas parcelas de tierra en diferentes zonas climáticas. Estas zonas van desde llanuras subtropicales hasta regiones alpinas. Los agricultores cultivan una variedad de cultivos. Esta diversidad geográfica ayuda a crear resiliencia frente a las incertidumbres climáticas. También destaca la importancia de la agrobiodiversidad para mantener la productividad agrícola y la seguridad alimentaria. Sin embargo, los pequeños agricultores de Nepal se enfrentan a numerosos desafíos que amenazan sus medios de vida y obstaculizan la productividad agrícola. El acceso limitado a la tecnología moderna, los patrones climáticos impredecibles y las prácticas agrícolas tradicionales ineficientes son las principales preocupaciones. Estos factores contribuyen a la incertidumbre en la productividad agrícola, la inestabilidad económica y las pérdidas significativas antes y después de la cosecha. Estos desafíos exacerban la pobreza rural y, a menudo, conducen a la emigración de jóvenes en busca de mejores oportunidades económicas, lo que deja a las comunidades agrícolas con escasez de mano de obra y cambios demográficos.

En respuesta a estos desafíos, existe una necesidad urgente de soluciones innovadoras y asequibles para mejorar la productividad y la sostenibilidad de la agricultura a pequeña escala. El Internet de las Cosas (IoT) surge como una solución tecnológica prometedora que cierra la brecha entre las prácticas agrícolas tradicionales y la tecnología moderna. La tecnología IoT permite a los agricultores monitorizar parámetros cruciales como la humedad del suelo, la temperatura y la salud de los cultivos en tiempo real. Este enfoque basado en datos permite a los agricultores tomar decisiones informadas con respecto al riego, la aplicación de fertilizantes, el manejo de plagas y otras prácticas agrícolas. Estas técnicas de agricultura de precisión no solo optimizan el uso de los recursos, sino que también ayudan a mitigar los riesgos asociados con la variabilidad climática y los factores ambientales. Además, el IoT facilita un mejor acceso al mercado a través de sistemas de trazabilidad e información del mercado en tiempo real. Estas innovaciones permiten a los agricultores conectarse directamente con los mercados, mejorar la eficiencia de la cadena de suministro y negociar mejores precios para sus productos. Para los pequeños agricultores que a menudo luchan con la integración del mercado y enfrentan desafíos para acceder a información oportuna sobre el mercado, el IoT puede mejorar significativamente la rentabilidad y potenciar la toma de decisiones.

Para diseñar e implementar de manera efectiva sistemas de IoT para pequeños agricultores y agricultura de precisión en Nepal, en este estudio se han identificado varios factores clave. Lo primero y más importante es la rentabilidad: el sistema debe ser asequible para los pequeños agricultores, incorporando sensores de bajo coste e infraestructura escalable en la nube. Esto garantiza la accesibilidad para los agricultores con recursos financieros limitados. La fiabilidad es otro factor crítico. Dados los desafíos con la electricidad y la conectividad a Internet en las áreas rurales, el sistema de IoT debe ser lo suficientemente robusto como para manejar condiciones intermitentes. Esto incluye el diseño de sistemas que puedan funcionar de manera eficiente a pesar de los cortes de energía o la disponibilidad limitada de la red. La facilidad de uso es esencial para la adopción generalizada de los sistemas de IoT, especialmente para los pequeños agricultores. El sistema debe tener una interfaz de usuario simple, que requiera un conocimiento técnico mínimo para operar. Esto hace que la tecnología sea accesible a una amplia gama de usuarios, incluidos aquellos con experiencia limitada con herramientas digitales. La personalización es crucial para abordar las diversas necesidades de los diferentes cultivos y ganado. Los sistemas de IoT deben ser adaptables, garantizando una amplia aplicabilidad en diversos contextos agrícolas. Esto permite a los agricultores adaptar la tecnología a sus necesidades específicas, mejorando su eficacia. La seguridad de los datos es primordial para ganarse la confianza de los agricultores. Garantizar la seguridad y privacidad de los datos recopilados protege la información confidencial y genera confianza en el sistema.

La plataforma de IoT propuesta para los pequeños agricultores presenta atractivas aplicaciones del mundo real en varios escenarios agrícolas. Algunas de estas aplicaciones incluyen:

Agricultura de túneles de invernaderos: La adopción de túneles de invernaderos para el cultivo de cultivos va en aumento. Dentro de estos entornos controlados, la plataforma IoT ofrece una gestión eficaz de las condiciones climáticas y el riego, lo que en última instancia conduce a una mayor productividad y mayores beneficios para los agricultores. Operaciones de vivero (plantas frutales y florales): El injerto de plantas frutales y florales en un vivero exige un meticuloso control interno del microclima. La plataforma IoT proporciona una solución ideal para gestionar estas condiciones, asegurando un crecimiento y desarrollo óptimos de las plantas. Además, se puede realizar un injerto fuera de temporada para extender el período de injerto y satisfacer la demanda de árboles jóvenes injertados. Cultivo de hongos: El cultivo de hongos es popular entre los pequeños agricultores en Nepal debido a su rápida respuesta y rentabilidad. La plataforma IoT puede desempeñar un papel fundamental en el cultivo de hongos al permitir un control preciso de factores ambientales como la temperatura, la humedad y la intensidad de la luz, que son críticos para el crecimiento exitoso de los hongos. Avicultura: Un número significativo de pequeños agricultores en Nepal operan granjas avícolas a pequeña escala. La plataforma IoT facilita el monitoreo remoto en tiempo real de parámetros cruciales dentro de la granja avícola, incluida la temperatura, la humedad y la calidad del aire. También se puede emplear para automatizar los sistemas de alimentación y agua. Además, los sistemas de calefacción, refrigeración e iluminación en tiempo real se pueden automatizar para optimizar el consumo de energía. Seguridad de la granja y control de acceso: Garantizar la seguridad y el acceso controlado a las instalaciones de un agricultor es de gran importancia. La plataforma IoT se puede utilizar para este propósito. La integración de sensores y actuadores, como sensores de movimiento y alarmas, proporciona una detección temprana de intrusiones y protege la granja.

Principales aportaciones de la tesis

Las contribuciones clave de este estudio incluyen el diseño de una plataforma de IoT personalizada para los pequeños agricultores en Nepal, centrándose en un enfoque de bajo costo, localizado, confiable y de intercambio comunitario. La plataforma está desarrollada para admitir aplicaciones web y móviles. Para validar la fiabilidad y robustez de la plataforma, se llevaron a cabo experimentos de campo con diferentes datos de sensores relacionados con la agricultura durante un período significativo. Este estudio también incluye un estudio de caso mediante la implementación de la plataforma IoT en escenarios del mundo real para el injerto fuera de temporada de cítricos y el almacenamiento posterior a la cosecha. Los resultados de la metodología y el enfoque fueron los esperados y cumplieron con los objetivos de la investigación.

La investigación sienta las bases para futuros estudios centrados en la innovación y el perfeccionamiento de los sistemas agrícolas basados en IoT para pequeños agricultores y agricultores comunitarios en países en desarrollo como Nepal. Las oportunidades incluyen un mayor desarrollo de la plataforma IoT, la exploración de nuevas aplicaciones y la integración con tecnologías emergentes como la inteligencia artificial, *Bigdata* y *blockchain*. Los estudios futuros realizados durante un período más largo pueden evaluar cómo las intervenciones de IoT afectan los medios de vida, la resiliencia y la sostenibilidad de los pequeños agricultores. Comprender cómo se adopta la tecnología y sus efectos socioeconómicos dentro de las comunidades agrícolas será un enfoque clave. Además, la comparación de diferentes regiones o países puede proporcionar información sobre los factores que influyen en la adopción de IoT en la agricultura. Esta comparación puede ayudar a ampliar las intervenciones exitosas e identificar las mejores prácticas. En general, la tesis tiene como objetivo contribuir con conocimientos integrales y soluciones prácticas para mejorar la productividad agrícola, la sostenibilidad y el desarrollo socioeconómico en las comunidades de pequeños agricultores de Nepal a través de la tecnología IoT.

Organización de la memoria de tesis

Esta tesis está estructurada en cinco capítulos. La tesis comienza con un capítulo introductorio que aborda los desafíos que prevalecen en la agricultura nepalí, particularmente entre los pequeños agricultores. Articula la necesidad de soluciones de IoT personalizadas para abordar estos desafíos y establece la importancia de la investigación. El capítulo describe los objetivos, la motivación, el alcance y la organización del estudio, proporcionando una hoja de ruta para los capítulos siguientes. El capítulo de revisión de la literatura examina la investigación existente sobre las aplicaciones de IoT en la agricultura, tanto a nivel mundial como en Nepal. Explora las características únicas de la agricultura a pequeña escala en Nepal y evalúa la eficacia de las soluciones actuales de IoT. También se analizan los desafíos y oportunidades de la adopción de tecnologías de IoT en la agricultura nepalí. El capítulo 3 describe el diseño y la implementación de la plataforma del sistema IoT y sus características. Profundiza en la conceptualización de la arquitectura del sistema IoT y su implementación. Cubre la configuración de hardware, el desarrollo de software y los procedimientos de prueba. Este capítulo también proporciona la posible inclusión de la plataforma en un escenario de caso de uso del mundo real. El capítulo 4 se centra en estudios de casos y ensayos de campo, examina el rendimiento del sistema IoT en condiciones agrícolas del mundo real. Se analiza la selección de los sitios piloto, los métodos de recopilación de datos, la retroalimentación de los usuarios y la evaluación del impacto del sistema en las prácticas agrícolas. A través de estudios de caso y ensayos de campo en injerto fuera de temporada y almacenamiento pre y post cosecha de cítricos, este capítulo ofrece evidencia empírica de la efectividad y los beneficios potenciales del sistema.

Finalmente, el capítulo 5 sirve como conclusión y ofrece ideas sobre las direcciones futuras. Resume los principales hallazgos y contribuciones de la investigación. El capítulo concluye reafirmando la importancia de la investigación para avanzar en el desarrollo agrícola en Nepal y subraya la importancia de la innovación y la colaboración continuas para aprovechar el potencial de la tecnología IoT en beneficio de los pequeños agricultores.

Contenido del capítulo 2

Esta sección de la tesis se ocupa de la revisión de la literatura relevante y los antecedentes necesarios para llevar a cabo la investigación. Lo más destacado se centra en varios aspectos del Internet de las cosas. Comenzando con los fundamentos de Internet de las cosas, sensores y dispositivos, arquitectura de la capa de IoT, varios protocolos de IoT y conectividad, también se destaca sobre los principales campos de aplicación de IoT. Además, también cubre el modelo de IoT basado en la nube y los proveedores de servicios. Posteriormente, la concentración de esta sección se centra en el IoT y su adopción en la agricultura. También resume brevemente el dominio de IoT en la agricultura, como la agricultura de precisión, la agricultura inteligente, la agricultura digital, la automatización de granjas, la agricultura conectada IoT (AIoT), la agricultura basada en sensores, la teledetección en la agricultura.

La integración de la tecnología de Internet de las cosas (IoT) en la agricultura, conocida como operaciones agrícolas basadas en IoT, está revolucionando las prácticas agrícolas en todo el mundo. Esta transformación está impulsada por la necesidad de aumentar la productividad agrícola, optimizar el uso de los recursos y mitigar el impacto ambiental frente a desafíos globales como el crecimiento de la población, el cambio climático y la seguridad alimentaria. Las arquitecturas de IoT en la agricultura generalmente involucran redes de sensores y actuadores desplegados en las granjas para monitorizar y administrar varios aspectos del crecimiento de los cultivos, las condiciones del suelo, los parámetros ambientales y la salud del ganado. Estos sensores recopilan datos en tiempo real sobre la humedad del suelo, la temperatura, la humedad y la salud de los cultivos, que se transmiten a sistemas centralizados o servidores y plataformas basados en la nube para su análisis. La computación en la niebla o en el borde desempeña un papel crucial al procesar los datos más cerca de donde se generan, lo que reduce la latencia y permite una toma de decisiones más rápida.

La agricultura de precisión es una aplicación fundamental de IoT en la agricultura, que permite a los agricultores adaptar sus prácticas en función de datos precisos. Mediante el uso de sensores de IoT para monitorizar y analizar las condiciones del campo, los agricultores pueden optimizar los programas de riego, aplicar fertilizantes y pesticidas de manera más eficiente y predecir enfermedades de los cultivos. Este enfoque específico no solo mejora el rendimiento y la calidad de los cultivos, sino que también minimiza el desperdicio de insumos y el impacto ambiental. La agricultura inteligente lleva la agricultura de precisión un paso más allá al integrar el IoT con la inteligencia artificial (IA) y el análisis de datos. Los algoritmos de IA analizan grandes volúmenes de datos generados por IoT para proporcionar información predictiva y recomendaciones para optimizar las operaciones agrícolas. Por ejemplo, los modelos predictivos pueden pronosticar el rendimiento de los cultivos en función de los patrones climáticos y recomendar momentos óptimos de siembra y programas de cosecha.

Los protocolos y estándares de IoT garantizan una comunicación fluida entre dispositivos y sistemas. Los protocolos ampliamente utilizados incluyen HTTP / HTTPS, MQTT, CoAP, Zigbee, BLE, LoRaWAN y 6LoWPAN. La elección entre ellos depende de requisitos específicos como el consumo de energía, el rango de comunicación, la escalabilidad y la seguridad. La descripción del estado del arte de estos protocolos se resume en la tesis.

Las opciones de conectividad de IoT incluyen soluciones cableadas e inalámbricas. La conectividad por cable utiliza cables físicos como Ethernet y conexiones en serie (RS-232/RS-485), lo que ofrece una alta fiabilidad y velocidades de datos. Son adecuados para entornos estables, pero menos flexibles para el uso móvil. Las opciones inalámbricas varían: Wi-Fi proporciona altas velocidades de datos localmente, pero problemas de alcance e interferencia limitados; Bluetooth admite la comunicación de corto alcance para dispositivos portátiles; Las redes celulares (3G/4G/5G) ofrecen una amplia cobertura para dispositivos IoT remotos o móviles. Las redes de área amplia (LPWAN) de baja potencia como LoRa, Sigfox y NB-IoT satisfacen las necesidades de largo alcance y baja potencia en aplicaciones como la agricultura inteligente, lo que garantiza la conectividad a grandes distancias con un consumo mínimo de energía.

Las plataformas de IoT son esenciales para la gestión de dispositivos conectados, el procesamiento de datos y el desarrollo de aplicaciones dentro del ecosistema de IoT. Son cruciales para escalar proyectos de IoT en diversas industrias, facilitar la innovación e impulsar la transformación digital. En la agricultura, las plataformas de IoT en la nube como AWS IoT y Azure IoT Hub ofrecen amplias integraciones dentro de sus ecosistemas, lo que proporciona flexibilidad y escalabilidad. Plataformas como ThingSpeak hacen hincapié en la visualización de datos y son adecuadas para proyectos agrícolas de menor escala. Estas plataformas permiten la gestión de dispositivos, la recopilación de datos y el análisis, con diferentes niveles de capacidades específicas de la industria. Las características avanzadas de plataformas como Azure Farm Beat, Google Cloud IoT e IBM Watson IoT incluyen IA y aprendizaje automático, lo que mejora la información basada en datos para aplicaciones agrícolas. En general, las plataformas de IoT basadas en la nube desempeñan un papel fundamental en la agricultura moderna al permitir una conectividad, supervisión y análisis sin interrupciones de los datos de los dispositivos IoT.

Contenido del capítulo 3

Varios estudios de casos destacan las aplicaciones prácticas y los beneficios de IoT en la agricultura. Por ejemplo, la agricultura de precisión habilitada para IoT se ha implementado con éxito en los viñedos para monitorizar la humedad y la temperatura del suelo, lo que mejora la eficiencia del riego y la producción de uva. En la ganadería, los sistemas de monitorización basados en IoT realizan un seguimiento de la salud y el comportamiento de los animales en tiempo real, lo que mejora la gestión de la cría y la producción de leche. Los drones equipados con sensores y cámaras IoT se utilizan en el monitoreo de la salud de los cultivos para detectar temprano infestaciones de plagas y deficiencias de nutrientes, lo que permite intervenciones oportunas y mayores rendimientos.

Persisten desafíos en la adopción generalizada de IoT en la agricultura, incluidos los costos iniciales de la infraestructura de IoT, los problemas de conectividad en las áreas rurales y las preocupaciones sobre la privacidad y la seguridad de los datos. Abordar estos desafíos requiere inversiones en desarrollo de infraestructura, apoyo a las políticas y educación de los agricultores. Mejorar la conectividad a Internet y el acceso a tecnologías de IoT asequibles son pasos críticos para permitir que los pequeños agricultores se beneficien de las innovaciones de IoT.

La arquitectura de IoT propuesta para la agricultura a pequeña escala representa un avance significativo en la integración de la tecnología para mejorar las prácticas agrícolas. Incorpora un sólido sistema de redes de sensores, capacidades de computación periférica e infraestructura en la nube diseñada específicamente para los pequeños agricultores. Diseñada para ser asequible y fácil de usar, la arquitectura permite a los agricultores con recursos limitados acceder y beneficiarse de soluciones tecnológicas avanzadas. Esta escalabilidad garantiza que el sistema pueda adaptarse a las necesidades cambiantes de los agricultores, proporcionando flexibilidad en la selección de los servicios de aplicación que mejor se adapten a sus requisitos específicos.

En la figura 1 se muestra el enfoque personalizado de la plataforma de IoT. Destaca cómo la plataforma es adaptable y personalizable. Los usuarios pueden ajustar el sistema para satisfacer sus necesidades específicas. Esta flexibilidad se aplica tanto a los servicios de sensores como a los de interruptores. Los agricultores pueden desplegar sensores para monitorizar las condiciones ambientales o usar interruptores para controlar los sistemas de riego y la configuración climática en los invernaderos. La plataforma permite a los agricultores configurarlo en función de sus preferencias operativas.

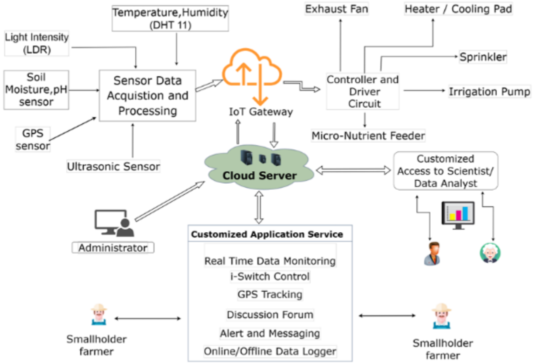

Figura 1 Plataforma de IoT personalizada

Un elemento central de la arquitectura propuesta es la estructura de aplicaciones y servicios centrada en el usuario, que facilita el acceso basado en roles y la implementación de dispositivos sin problemas. Los administradores desempeñan un papel crucial en la creación de distintos roles de usuario, que abarcan agricultores, usuarios personalizados, científicos y analistas de datos. Los usuarios finales están equipados con las herramientas para configurar dispositivos IoT en sus campos y administrar los datos recopilados de varios sensores. Estos datos, incluidos parámetros cruciales como la temperatura, la humedad, la humedad del suelo y los niveles de pH, se recopilan, procesan y transmiten meticulosamente a los servidores en la nube para su almacenamiento y análisis seguros.

Las características clave dentro del sistema propuesto mejoran significativamente las operaciones agrícolas. El monitoreo y la visualización de datos en tiempo real permiten a los agricultores tomar decisiones informadas con prontitud. A través de aplicaciones como "i-Switch", los agricultores pueden controlar de forma remota dispositivos críticos para sus operaciones, lo que garantiza una regulación precisa de los microclimas esenciales para el crecimiento óptimo de los cultivos. El seguimiento por GPS permite el seguimiento en tiempo real de los activos agrícolas, lo que mejora la eficiencia logística y la gestión de los activos. Las alertas y los sistemas de mensajería notifican a los usuarios de eventos críticos, ayudándoles a responder rápidamente a los cambios en su entorno agrícola.

El registro y el análisis de datos forman una piedra angular del sistema, proporcionando a los agricultores información completa sobre sus prácticas agrícolas. La arquitectura admite el registro de datos tanto in situ como en línea, lo que garantiza la disponibilidad de los datos incluso en áreas con una conectividad a Internet poco fiable. Este enfoque híbrido combina el almacenamiento local con soluciones basadas en la nube, lo que permite la recopilación y el análisis continuos de datos. La integración de un foro de discusión dedicado enriquece aún más la experiencia del usuario, fomentando el intercambio de conocimientos entre agricultores, investigadores y expertos.

Los componentes de hardware y diseño de aplicaciones del sistema propuesto se eligen para maximizar la funcionalidad y la eficiencia. Las unidades de microcontrolador como el NodeMCU ESP8266 con conectividad Wi-Fi se utilizan para una transmisión de datos rentable y fiable. Los sensores y actuadores recopilan y controlan los parámetros ambientales, lo que respalda la agricultura de precisión adaptada a las condiciones agrícolas locales. Los datos se administran en los servicios en la nube de Microsoft Azure, lo que garantiza la escalabilidad, la seguridad y la accesibilidad. Esta configuración se adapta a diversas preferencias de los usuarios y funciona en plataformas web y móviles.

Se llevan a cabo pruebas de rendimiento y análisis comparativos para mostrar la solidez y rentabilidad de la plataforma IoT propuesta. Las pruebas de carga del servidor confirman la fiabilidad del sistema bajo diferentes cargas de usuarios. Los estudios comparativos con otras plataformas de IoT existentes destacan la rentabilidad y la usabilidad del sistema de IoT propuesto. Esto lo hace accesible para los pequeños agricultores que desean optimizar sus operaciones agrícolas utilizando la tecnología IoT. Las implementaciones en el mundo real, como el monitoreo y la regulación de microclimas dentro de los invernaderos, validan los beneficios prácticos de la plataforma IoT. La implementación y los resultados mostraron que la arquitectura de IoT propuesta es confiable y efectiva para proporcionar a los pequeños agricultores datos y control en tiempo real para mejorar la eficiencia y la productividad de sus operaciones agrícolas. Sin embargo, también existen desafíos para su implementación, como la voluntad de los pequeños agricultores de adoptar la tecnología, la capacitación y el apoyo de la comunidad, y una mayor reducción de los costos y la capacidad técnica para una operación adecuada.

La arquitectura de software del sistema IoT propuesto garantiza una gestión eficiente de los dispositivos, la seguridad y la comunicación en tiempo real. La API facilita la autenticación, la autorización y el intercambio de datos a través de los puntos finales de la API REST. La autenticación de usuario utiliza el ID de usuario, la contraseña y el ID de cliente, mientras que la autorización basada en roles regula el acceso. El *front-end*, construido con ASP.NET MVC, incluye un panel dinámico para la visualización de datos en tiempo real y SignalR para la comunicación en tiempo real. La aplicación móvil, desarrollada con Flutter, ofrece una experiencia perfecta en Android, lo que permite a los usuarios visualizar datos y controlar la configuración de forma remota. Los datos se almacenan en una base de datos de SQL Server y todo el sistema se aloja en Microsoft Azure, lo que garantiza una alta disponibilidad, escalabilidad y recuperación ante desastres. La arquitectura ajusta dinámicamente los recursos para manejar diferentes cargas de trabajo de manera eficiente.

Contenido del capítulo 4

La memoria de tesis continúa con un estudio de caso con la implementación del sistema propuesto en injerto de invernadero y cámara fría para el almacenamiento postcosecha en las regiones montañosas de Nepal. El cultivo de cítricos, especialmente mandarinas, es crucial para la economía de las regiones montañosas de Nepal debido a sus condiciones geoclimáticas ideales. A pesar de su importancia económica, el sector se enfrenta a varios desafíos, como técnicas de injerto inadecuadas, árboles jóvenes de baja calidad y almacenamiento postcosecha ineficaz. El estudio llevado a cabo en esta tesis explora estas cuestiones y propone soluciones innovadoras utilizando la tecnología de Internet de las Cosas (IoT) propuesta. Para abordar estos desafíos, identificamos áreas clave de mejora. En primer lugar, nos centramos en ampliar las prácticas de injerto durante la temporada baja para garantizar una mayor tasa de éxito y árboles jóvenes de mejor calidad. En segundo lugar, examinamos diferentes métodos de almacenamiento postcosecha para determinar su eficacia en términos de vida útil, pérdida por descomposición y calidad de la fruta. Además de explorar las estrategias de postcosecha, este estudio proporciona recomendaciones previas a la cosecha para los agricultores, haciendo hincapié en los métodos para mejorar la calidad y la longevidad de la fruta a través de prácticas efectivas de pre-almacenamiento. La Figura 2 muestra nuestro enfoque basado en IoT para el injerto fuera de temporada en invernaderos y el monitoreo avanzado para el almacenamiento posterior a la cosecha.

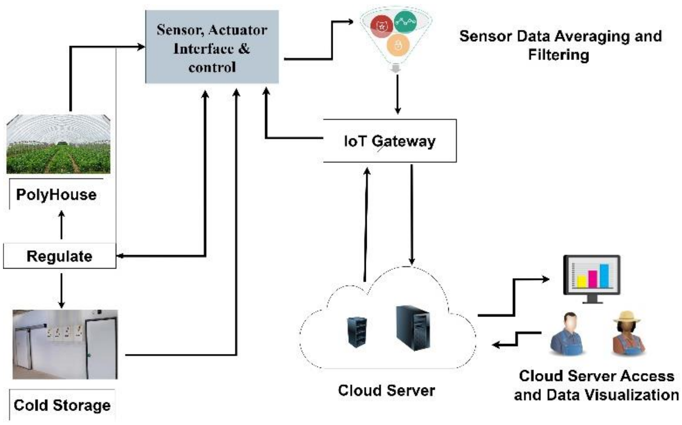

Figura 2 Sistema IoT para monitorización y control de invernadero y almacenamiento en frío

La implementación de la tecnología IoT en el injerto fuera de temporada es un concepto relativamente nuevo e innovador en el contexto de Nepal. Tradicionalmente limitado por las condiciones climáticas estacionales, el injerto de cítricos ahora puede ocurrir durante todo el año dentro de invernaderos equipados con dispositivos IoT. Estos dispositivos monitorean parámetros críticos como la temperatura, la humedad y los niveles de luz, creando condiciones óptimas para un injerto exitoso incluso cuando el clima externo es desfavorable. Este control ambiental preciso reduce los riesgos asociados con una mala unión del injerto y mejora las tasas de supervivencia de las plantas injertadas.

Un elemento central del estudio es la selección de métodos de injerto apropiados y combinaciones de vástagos y portainjertos adaptadas a las condiciones locales. El injerto de chapa con portainjertos trifoliados ha demostrado ser muy exitoso para las variedades de lima ácida y mandarina en las regiones montañosas de Nepal. Se lograron tasas de éxito de injerto del 91% para la cal ácida y del 92% para las variedades locales de mandarina. Este enfoque metodológico no solo extiende la temporada de injerto, sino que también garantiza árboles jóvenes de mayor calidad, abordando un desafío de larga data en la comunidad de productores de cítricos.

Más allá del injerto, el estudio hace hincapié en la optimización de las prácticas de manejo postcosecha, especialmente para las mandarinas. La tecnología IoT con monitoreo en tiempo real dentro de las cámaras frigoríficas permite un control ambiental preciso y respuestas inmediatas a las desviaciones, asegurando condiciones óptimas de almacenamiento y minimizando las pérdidas posteriores a la cosecha. Esta integración no solo mejora la eficiencia del almacenamiento, sino que también mejora la viabilidad económica de la citricultura al reducir el desperdicio y ampliar la disponibilidad en el mercado de productos de alta calidad.

Las recomendaciones previas a la cosecha incluyen el lavado de la superficie con agua limpia para eliminar los contaminantes y el tratamiento de las frutas con una solución de cloruro de calcio para mejorar la textura y la durabilidad durante el almacenamiento. La aplicación de cera de cítricos proporciona una capa protectora, crucial para mantener la frescura y evitar la pérdida de humedad, un paso crítico que a menudo los agricultores pasan por alto, pero esencial para preservar la calidad de la fruta. Además, nuestra investigación comparó diferentes métodos de almacenamiento postcosecha para mandarinas, incluyendo habitación, bodega y cámara frigorífica. Evaluamos estos métodos en función de la vida útil, la pérdida de peso fisiológica (PWL) y la relación entre sólidos solubles totales (SST) y acidez titulable (AT). La cámara de frío demostró ser el método más eficaz, ya que ofrece condiciones superiores para almacenar mandarinas durante más tiempo. El sistema de monitoreo basado en IoT desempeñó un papel crucial en el mantenimiento de la temperatura, la humedad y el contenido de gas óptimos dentro de la cámara frigorífica, lo que resultó en una reducción de las pérdidas posteriores a la cosecha y una vida útil prolongada. Estos hallazgos ponen de manifiesto el potencial transformador de la tecnología IoT en el cultivo de mandarinas y el almacenamiento postcosecha.

A pesar de su potencial transformador, el estudio reconoce sus limitaciones. Se llevó a cabo en las regiones montañosas específicas de Nepal, donde las condiciones geoclimáticas pueden diferir de las de otras regiones productoras de cítricos a nivel mundial, lo que limita la generalización de los hallazgos. Además, si bien la tecnología de IoT ofrece beneficios significativos, los costos iniciales de implementación y la necesidad de experiencia técnica pueden plantear desafíos, particularmente para los pequeños agricultores con recursos limitados. Al integrar las soluciones de IoT tanto en las etapas de injerto fuera de temporada como en las de almacenamiento posterior a la cosecha, los agricultores pueden aumentar la productividad, mejorar la calidad del producto y mejorar sus medios de vida. El estudio proporciona información práctica y recomendaciones para optimizar las prácticas agrícolas, haciendo hincapié en el papel de la tecnología en el fomento del crecimiento sostenible y la resiliencia en el sector citrícola. La investigación futura debe centrarse en la expansión de las aplicaciones de IoT para monitorizar y optimizar otros aspectos de la cría de cítricos, asegurando la innovación y el avance continuos en las prácticas agrícolas.

Conclusiones

Esta tesis explora el potencial transformador de IoT en la agricultura, centrándose en los desafíos y necesidades únicos de los pequeños agricultores en Nepal. El paisaje agrícola del país es diverso, abarca varias zonas climáticas y contribuye significativamente a los medios de vida de una gran parte de la población. El desarrollo de una plataforma de IoT adaptada a los pequeños agricultores nepalíes implica abordar varios parámetros críticos, como la rentabilidad, la fiabilidad, la escalabilidad, la personalización y la facilidad de uso. Estos factores son esenciales para garantizar que la tecnología sea accesible y beneficiosa para los agricultores que tienen recursos financieros limitados y diferentes niveles de conocimientos tecnológicos.

La tesis identifica desafíos significativos en el desarrollo de sistemas de IoT para la agricultura, particularmente en países de ingresos bajos y medios como Nepal. Las limitaciones de la infraestructura, como la falta de fiabilidad de la conectividad a Internet y del suministro de energía, plantean importantes obstáculos. Además, la falta de habilidades técnicas entre los agricultores, los altos costos de configuración inicial y la complejidad de administrar grandes volúmenes de datos son barreras sustanciales. A pesar de estos desafíos, la tecnología IoT es muy prometedora para mejorar la productividad agrícola, la eficiencia de los recursos y la resiliencia climática. Puede proporcionar datos en tiempo real que permiten a los agricultores tomar decisiones informadas, optimizar el uso de recursos y mejorar el rendimiento de los cultivos, aumentando así su productividad y rentabilidad generales.

Se llevó a cabo una revisión exhaustiva de la literatura para comprender el estado actual de IoT en la agricultura, identificar las brechas existentes y resaltar las áreas de innovación. Esta revisión sirvió de base para el desarrollo de una propuesta de sistema de IoT diseñado específicamente para los pequeños agricultores de Nepal. La arquitectura del sistema es rentable y personalizable, y utiliza unidades de microcontrolador de bajo costo como el NodeMCU ESP8266 con conectividad Wi-Fi para garantizar la asequibilidad y la transmisión de datos confiable. La arquitectura del software garantiza una gestión de datos segura y eficiente, con una interfaz fácil de usar a la que se puede acceder a través de plataformas web y móviles.

Las pruebas de rendimiento y el análisis comparativo con otras plataformas de IoT como Blynk y ThingSpeak demostraron la fiabilidad y las ventajas competitivas del sistema propuesto. Las pruebas de carga del servidor confirmaron la solidez del sistema bajo diferentes cargas de usuarios, y el análisis de costos subrayó su asequibilidad. La efectividad del sistema se validó aún más a través de un estudio de caso del mundo real realizado en un invernadero para el injerto fuera de temporada de cítricos. Este estudio demostró mejoras significativas en el monitoreo y regulación de las condiciones ambientales, lo que resultó en una mayor tasa de éxito del injerto y una mejor salud del cultivo. Además, el sistema IoT se utilizó para el almacenamiento previo y posterior a la cosecha de mandarinas, mostrando beneficios sustanciales para mantener condiciones óptimas de almacenamiento, reducir el deterioro y prolongar la vida útil del producto.

Los resultados de estos estudios ponen de manifiesto la aplicabilidad práctica y los beneficios del sistema IoT propuesto. Al proporcionar datos en tiempo real sobre parámetros ambientales críticos como la temperatura, la humedad y el contenido de gas, el sistema permite a los agricultores tomar decisiones oportunas e informadas. Esto conduce a un uso optimizado de los recursos, una mayor productividad y un mejor acceso a los mercados para los pequeños agricultores. La asequibilidad y escalabilidad del sistema lo hacen accesible a una amplia gama de usuarios, lo que garantiza que incluso aquellos con recursos limitados puedan beneficiarse de soluciones tecnológicas avanzadas.

En conclusión, esta tesis subraya el importante potencial de la tecnología IoT en la transformación de la agricultura para los pequeños agricultores en Nepal. Al abordar las necesidades y desafíos específicos de estos agricultores, el sistema de IoT propuesto ofrece una solución escalable, personalizable y rentable que mejora la productividad, la eficiencia de los recursos y la resiliencia climática. La implementación exitosa del sistema para el injerto y almacenamiento fuera de temporada de mandarinas demuestra su aplicabilidad práctica y efectividad. A medida que Nepal continúa modernizando sus prácticas agrícolas, la tecnología IoT desempeñará un papel crucial en el avance del desarrollo agrícola, la mejora de los medios de vida y la contribución al desarrollo sostenible del sector agrícola. Esta investigación destaca la importancia de la innovación y la colaboración continuas para aprovechar el potencial de la tecnología IoT en beneficio de los pequeños agricultores en Nepal.

Recomendaciones para investigaciones futuras: Las investigaciones futuras pueden basarse en esta tesis explorando varias áreas importantes. Se deben realizar estudios a largo plazo para evaluar el impacto sostenido de la IoT en los medios de vida y la resiliencia de los agricultores. La investigación debe centrarse en hacer que los sistemas de IoT sean más escalables y adaptables a diferentes cultivos y condiciones. La integración de IoT con tecnologías como la IA, la cadena de bloques y los drones puede abrir nuevas posibilidades. Las estrategias de reducción de costos son cruciales para hacer que el IoT sea accesible para los pequeños agricultores, incluida la exploración de subsidios y modelos comunitarios compartidos. El examen de los marcos normativos y normativos puede respaldar la adopción de IoT y, al mismo tiempo, garantizar la privacidad y la seguridad de los datos. Se deben desarrollar programas de capacitación para los agricultores para mejorar su comprensión y uso de la IoT. Evaluar el impacto ambiental de la tecnología IoT es importante para el desarrollo sostenible. Los estudios comparativos entre regiones y países pueden identificar las mejores prácticas y los modelos adaptables. Involucrar a las comunidades agrícolas en el proceso de investigación garantiza soluciones relevantes y efectivas. Por último, la gestión avanzada de datos y las medidas de ciberseguridad son esenciales para proteger la información sensible y garantizar la integridad de los datos. Al abordar estas áreas, la investigación futura puede mejorar aún más el potencial de la tecnología de IoT en la agricultura, beneficiando a los pequeños agricultores en Nepal y más allá.

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With heartfelt gratitude,

Ritu Raj Lamsal

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3G/4G/5G: Third Generation/Fourth Generation/Fifth Generation (mobile networks)
6LoWPAN: IPv6 over Low-Power Wireless Personal Area Networks
A0, A1, A2, A1v2: Azure cloud instances (types and configurations)
AI: Artificial Intelligence
ADS: Agricultural Development Strategy (2015–2035)
AMQP: Advanced Message Queuing Protocol
ANOVA: Analysis of Variance
API: Application Programming Interface
BLE: Bluetooth Low Energy
CoAP: Constrained Application Protocol
CSV: Comma-Separated Values
DDS: Data Distribution Service
DHT: Digital Humidity and Temperature sensor
DMRT: Duncan's Multiple Range Test
DOS: Days of Storage
ERP: Enterprise Resource Planning
GB: Gigabyte
GDP: Gross Domestic Product
GPS: Global Positioning System
HAT: Hot Air Treatment
HWD: Hot Water Dipping
HTTP: Hypertext Transfer Protocol
HTTPS: Hypertext Transfer Protocol Secure
I2C: Inter-Integrated Circuit
IFTTT: If This Then That
ICs: Integrated Circuits
ICT: Information and Communication Technology
IoT: Internet of Things
ISO/IEC/IEEE 42010:2011: International Standard for Architecture Description
KB: Kilobyte
kB/s: Kilobytes per second
LED: Light Emitting Diode
LoRa: Long Range
LoRaWAN: Long Range Wide Area Network
LPDE: Low-Density Polyethylene
LPWAN: Low-Power Wide-Area Network
LTE-M: Long-Term Evolution for Machines
LSD: Least Significant Difference
LSP: Light Saturation Point
MB: Megabyte
MQTT: Message Queuing Telemetry Transport

ms: Milliseconds
NB-IoT: Narrowband IoT
NCRP: National Citrus Research Program
NTP: Non-Thermal Plasma
NPR: Nepali Rupee
ns: Not Significant
PA: Precision Agriculture
PIR Motion Sensor: Passive Infrared Motion Sensor
PMAMP: Prime Minister Agriculture Modernization Project
PWL: Physiological Weight Loss
QoS: Quality of Service
REST API: Representational State Transfer Application Programming Interface
RFID: Radio-Frequency Identification
RS232: Recommended Standard 232
SMS: Short Message Service
SPI: Serial Peripheral Interface
TA: Titratable Acidity
TSS: Total Soluble Solids
UART: Universal Asynchronous Receiver-Transmitter
Wi-Fi: Wireless Fidelity
WSN: Wireless Sensor Network
XMPP: Extensible Messaging and Presence Protocol

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Chapter 1: Introduction

The Chapter introduces the agricultural landscape and the vital role of smallholder farmers in Nepal, emphasizing their significance and the challenges they face. It identifies essential factors for designing suitable Internet of Things system tailored to their needs, showcasing real-use cases and potential impacts. Section 1.3 highlights the motivation behind this research work. Section 1.4 outlines the objectives of the research. Section 1.5 discusses the significance and scope of the research. Section 1.6 details the thesis contributions. Section 1.7 presents the thesis organization. Finally, Section 1.8 lists related publications and conference presentations that support the research.

1.1. Transforming Agriculture with Internet of Things

The advent of the Internet of Things (IoT) has revolutionized several sectors by enabling real-time data collection, monitoring, and control through interconnected sensor devices. In agriculture, IoT offers promising solutions for optimizing resources, increasing productivity, and improving the sustainability of farming practices. The IoT is revolutionizing global agriculture by offering new ways to meet the increasing demand for food as the world's population grows. Agriculture is a cornerstone of Nepal’s economy. Despite its importance, the sector faces numerous challenges, including limited access to modern technology, inefficient traditional practices, and unpredictable climatic conditions. These challenges impact productivity, food security, and economic stability, particularly for smallholder farmers who manage a significant share of agricultural activities in Nepal.

The integration of IoT technology offers a transformative solution to these challenges. IoT enables real-time monitoring and control of agricultural parameters, such as temperature, humidity, soil moisture, soil nutrients, and crop health, through connected sensors and devices. This technology enhance decision-making, optimize use of resource, and improve productivity. For smallholder farmers, who often operate with constrained resources and face variable environmental conditions, IoT provides an opportunity to modernize agricultural practices affordably and effectively.

1.2. Global Food Security and the Agrarian Landscape of Nepal

The global population is projected to grow by almost 2 billion people over the next 30 years, increasing from 8 billion to 9.7 billion by 2050, which will intensify pressure on food production systems [1, 2]. Food security has become a major global concern, driven by population growth, sustainability challenges, and income inequality. Factors such as climate change, resource scarcity, and market dynamics significantly impact and disrupt production and distribution [3]. Addressing the food demand of a growing population will require innovative approaches, including the integration of modern technologies like the IoT, Artificial Intelligence (AI), and Big Data into agriculture to improve productivity and efficiency [4]. Nepal, with its rich agrarian tradition, is heavily reliant on agriculture, which contributes about 26% to the national GDP and engages nearly two-thirds of the population. Smallholder farmers, who typically manage less than 2 hectares of land, are crucial to the country's food security, rural livelihoods, and socio-economic stability [5, 6, 7]. They cultivate a variety of crops to mitigate risks from unpredictable weather and other adverse conditions. Nepal's unique geo-climatic conditions contribute to its rich agro-biodiversity, allowing farmers to grow a wide variety of crops [8]. The country's topography varies from the lowland Terai plains to the mid-hills and the high Himalayas. This diversity in elevation creates a range of climates from subtropical in the Terai to temperate in the mid-hills and alpine in the high mountains offering a broad spectrum of growing conditions. Farmers in Nepal use this geo-climatic diversity to cultivate crops that are best suited to their specific regions. The lower Terai plains, with their warm temperatures and fertile soil, are ideal for growing rice, sugarcane, and other subtropical vegetables and fruits. The mid-hills, with cooler temperatures and more varied terrain, are suitable for maize, millet, wheat, and fruit trees. In the high Himalayas, where the climate is harsh, farmers grow hardy crops like barley and buckwheat and fruit like apples. This varied climate also helps farmers hedge against unpredictable weather patterns and other adverse factors. If a particular crop fails due to unfavorable weather or pests, farmers can rely on other crops that are more resistant to such conditions. This diversification is a key strategy for ensuring food security and sustaining livelihoods in Nepal's often challenging environment [9, 10].

1.2.1 The Role of Smallholder Farming in agriculture

Agriculture plays a crucial role in the economies of lower- and middle-income countries, providing livelihoods for a significant portion of the population. In countries like Nepal, the agricultural sector is vital for food security, employment, and income generation. The economy survey highlighted that the major sectors contributing to the nation's GDP include agriculture, industry, and service sectors, which are estimated to contribute 24.1 percent, 13.5 percent, and 62.4 percent, respectively [11]. Agriculture is not only a source of food but also a means of subsistence for many rural families, supporting the livelihood of the majority of the rural population, driving rural economies, and creating employment opportunities. However, productivity levels have not kept pace with growing demands, leading to a widening gap between agricultural production and national requirements. Studies suggest that the nation's economy heavily depends on government expenditure on agriculture [12].

Smallholder farming in Nepal encompasses various aspects, including crop cultivation, livestock rearing, farming techniques, and socioeconomic conditions. The predominant crops in smallholder farms are subsistence crops such as rice, wheat, maize, millet, and barley, grown to meet household food needs. Alongside these staple crops, farmers also cultivate cash crops like vegetables, fruits, spices, tea, coffee, and pulses to generate income through market sales. Livestock rearing, including dairy farming, poultry, and animal husbandry, provides additional income and nutritional support. Traditional farming techniques, such as manual plowing, seed broadcasting, and organic fertilization, are widely used. Smallholder farmers rely on minimal machinery and family labor. These Farmers often use agroforestry which involves in mixing trees with crops or creating small orchards to diversify their income. Socioeconomic factors significantly impact smallholder farming. These factors include small and fragmented landholdings, poverty, and limited access to credit. Farmers also have limited access to market information and agricultural inputs. Rural outmigration, particularly among the youth, contributes to labor shortages and changing agricultural demographics. Gender dynamics also influence smallholder farming. Women play a crucial role in agricultural production. However, they have limited access to resources and decision-making power [13]. Despite these challenges, smallholder farming in Nepal continues to be a key component of the country's agricultural landscape, supporting livelihoods and contributing to food security.

1.2.2 Challenges Faced by Smallholder Farmers

Smallholder farmers face a numerous challenge, including limited access to modern agricultural technologies, inadequate infrastructure, and susceptibility to climatic variations [14]. These factors contribute to economic instability and limited opportunities for growth. In context of Nepal, the traditional farming practices they rely on are often resource-intensive and yield lower outputs. As a result, many young people migrate abroad in search of better employment, exacerbating labor shortages in agriculture. They often have limited access to crucial resources such as land, water, credit, and essential inputs like seeds and fertilizers, which impedes their ability to adopt modern farming practices and enhance productivity. Additionally, Nepal's agriculture sector is highly vulnerable to climate change, with erratic weather patterns, natural disasters, and environmental degradation posing substantial threats. Farmers, predominantly relying on rain-fed agriculture, are particularly susceptible to the adverse effects of climate variability. Agricultural productivity remains low, primarily due to outdated farming techniques, inadequate infrastructure, and poor market access. Post-harvest losses are significant, exacerbated by inefficient storage and transportation systems, resulting in substantial food waste and reduced incomes for farmers. Furthermore, smallholder farmers often lack access to timely and accurate information on weather forecasts, market prices, pest management, and best agricultural practices.

1.2.3 Opportunities and Challenges of Adopting IoT in Nepalese Agriculture

In the past, Nepal's farming system faced numerous challenges, including small land holdings, inadequate irrigation, limited access to fertilizers, and a lack of mechanization and modern technology. However, as the global trend shifts towards modern and precision farming, the agricultural landscape in Nepal is also evolving. Innovative approaches such as integrated, cluster-based, cooperative, and commercial farming are gaining traction.

Embracing technology is crucial for sustainable agricultural development, presenting an opportunity to enhance production efficiency. While much of the advancements in sensor and IoT technology have originated in developed countries, there's growing recognition of its potential impact in Nepal's agricultural context. Previous research has highlighted the positive outcomes associated with deploying IoT sensors in agriculture, indicating promising prospects for the sector's future development. For many years, the Nepal government has been focusing on improving agricultural production and commercialization by introducing some key plans and strategies. The government's recent initiative is the Prime Minister Agriculture Modernization Project, Agricultural Development Strategy (2015–2035), which aims to implement modern technology to enhance agricultural productivity and commercialization [15]. In this context, there's a growing recognition of the potential of innovative technologies like the IoT and mechanization to empower smallholder farmers. The adoption of IoT technologies in Nepalese agriculture presents significant potential but also faces several challenges. Highlighting the potential benefits and opportunities for IoT integration is crucial, followed by identifying specific barriers and strategies to address them. IoT technologies offer significant opportunities to enhance productivity and resilience in Nepalese agriculture.

Precision agriculture, enabled by IoT, allows farmers to collect real-time data on crucial parameters such as soil moisture, temperature, and crop health. This detailed information enables them to optimize resource use and increase crop yields while minimizing inputs. Additionally, IoT-based decision support systems provide farmers with customized insights and recommendations for irrigation, fertilizer application, pest control, and crop management, using localized data and predictive analytics. Furthermore, IoT technologies can enable early warning systems, helping farmers anticipate and mitigate the impact of extreme weather events, such as floods, droughts, and landslides, on agricultural production and livelihoods.

Improving market access and value chains is another area where IoT can play a transformative role. IoT-enabled traceability systems can improve transparency and accountability in agricultural value chains, facilitating access to markets and premium prices for certified products, such as organic produce or fair-trade commodities [16]. Moreover, IoT-based market information services can provide smallholder farmers with real-time market prices, demand forecasts, and supply chain logistics, enabling informed decision-making and better market participation. This can lead to better prices for their produce and empower farmers with greater bargaining power.

IoT technologies can also strengthen extension services and farmer support. Digital extension services can enhance agricultural extension by providing farmers with access to personalized advice, best practices, and training materials through mobile applications, SMS alerts, and interactive voice response systems. Additionally, IoT-enabled farmer cooperatives and collectives can leverage collective action and shared resources to pool investments, negotiate better prices for inputs and outputs, and access financing and insurance services. This collective approach can help smallholder farmers overcome individual limitations and achieve greater efficiency and productivity. Fostering innovation and collaboration is another critical opportunity presented by IoT. Collaboration between government agencies, research institutions, technology developers, and farmer organizations can drive research and development on context-appropriate IoT solutions tailored to the needs of Nepalese agriculture. Public-private partnerships can facilitate the co-creation and deployment of IoT technologies in agriculture, leveraging the strengths of both public sector agencies and private sector companies to drive innovation and scale up adoption. Such partnerships can ensure that IoT solutions are both technically viable and commercially sustainable.

Despite these opportunities, there are several challenges that need to be addressed to facilitate the adoption of IoT in Nepalese agriculture. Infrastructural constraints are a significant barrier. Many rural areas in Nepal lack access to reliable internet connectivity and mobile networks, hindering the implementation of IoT solutions that require real-time data transmission and communication. Additionally, irregular electricity supply and inadequate infrastructure for renewable energy sources pose challenges for deploying IoT devices, particularly in remote farming communities where access to electricity is limited. Lack of awareness and technical skills among smallholder farmers is another major challenge. Many farmers in Nepal may have limited knowledge and awareness of IoT technologies and their potential applications in agriculture, leading to skepticism and reluctance to adopt new technologies. Furthermore, farmers and agricultural extension workers may lack the technical skills and training required to install, operate, and maintain IoT systems, including sensor calibration, data interpretation, and troubleshooting.

Affordability and cost-benefit concerns also hinder IoT adoption. The upfront costs associated with purchasing IoT sensors, communication infrastructure, and data analytics platforms may be prohibitive for smallholder farmers with limited financial resources, leading to concerns about the return on investment. Farmers may be hesitant to invest in IoT technologies without clear evidence of their potential benefits in terms of increased productivity, cost savings, and improved livelihoods, especially given the unpredictable nature of agriculture. Policy and regulatory challenges further complicate the adoption of IoT in agriculture. The absence of clear policies and regulatory frameworks governing the use of IoT technologies in agriculture may create uncertainty and inhibit investment and innovation in the sector. Additionally, farmers may have concerns about data privacy and security, particularly regarding the collection, storage, and sharing of sensitive agricultural data collected by IoT devices.

To address these challenges, several strategies can be implemented. Improving infrastructure is crucial. Investing in enhancing internet connectivity and mobile network coverage in rural areas is essential to support real-time data transmission and communication for IoT solutions. Additionally, developing infrastructure for reliable electricity supply and exploring renewable energy sources can ensure continuous operation of IoT devices in remote areas. Raising awareness and building technical skills is also vital. Implementing educational and training programs to increase awareness about IoT technologies and their benefits can encourage adoption. Providing technical training to farmers and extension workers on installing, operating, and maintaining IoT systems is equally important. Conducting demonstration projects to showcase the practical benefits of IoT in agriculture can further encourage adoption through visible success stories.

Addressing affordability concerns is another important strategy. Providing subsidies or financial support to smallholder farmers can reduce the initial costs of IoT adoption. Exploring microfinancing options can make IoT technologies more accessible. Collecting and disseminating data on the cost-benefit analysis of IoT adoption in agriculture can build confidence among farmers regarding the potential returns on investment.

1.2.4 Key Factors in Designing IoT Systems for Agriculture in Nepal

To effectively implement IoT systems for smallholder and precision farming in Nepal, several key factors must be considered. First and foremost is cost-effectiveness: the system should be affordable for smallholder farmers, incorporating low-cost sensors and scalable cloud infrastructure. This ensures accessibility for farmers with limited financial resources. Reliability is another critical factor. Given the challenges with electricity and internet connectivity in rural areas, the IoT system must be robust enough to handle intermittent conditions. This includes designing systems that can operate efficiently despite power outages or limited network availability. User-friendliness is essential for the widespread adoption of IoT systems. The system should have a simple user interface, requiring minimal technical knowledge to operate. This makes the technology accessible to a broad range of users, including those with limited experience with digital tools. Customization is crucial to address the diverse needs of different crops and livestock. IoT systems should be adaptable, ensuring broad applicability across various agricultural contexts. This allows farmers to tailor the technology to their specific requirements, enhancing its effectiveness. Data security is paramount for gaining the trust of farmers. Ensuring the security and privacy of collected data protects sensitive information and builds confidence in the system. Farmers need to feel assured that their data will not be misused or accessed without their consent.

The societal impact and sustainability of IoT adoption in Nepalese agriculture extend beyond individual benefits. By improving productivity and efficiency, IoT can help create a more sustainable agricultural sector. This contributes to food security, reduces the need for migration among young people, and helps stabilize rural communities. Moreover, IoT supports environmental sustainability by optimizing resource use and reducing waste. Looking to the future, the integration of IoT in Nepalese agriculture has the potential to transform smallholder and precision farming, addressing key challenges and opening new opportunities. While there are hurdles to overcome, focusing on cost-effectiveness, community-based approaches, and robust design can lead to a more sustainable and productive agricultural sector. As data connectivity and electricity reach more rural areas, the possibilities for IoT in agriculture are substantial, providing a pathway to a more efficient and resilient future for Nepal's smallholder farmers.

1.2.5 Real Use Case Scenario from Smallholder’s Perspective

The study conducted during the research has proposed several real-world applications of IoT platforms for the smallholder farmers across various agricultural scenarios.

i. Mushroom Farming: Mushroom cultivation is popular among smallholder farmers in Nepal due to its quick turnaround and profitability. The IoT platform can play a pivotal role in mushroom farming by enabling precise control of environmental factors such as temperature, humidity, and light which are critical for successful mushroom growth.

ii. Polyhouse Tunnel Agriculture: The adoption of polyhouse tunnels for tomato cultivation is on the rise. Within these controlled environments, the IoT platform offers effective management of climatic conditions and irrigation, ultimately leading to increased productivity and higher profits for farmers.

iii. Nursery Operations (Fruit and Flower Plants): Grafting fruit and flower plants in a nursery demands meticulous internal microclimate control. The IoT platform provides an ideal solution for managing these conditions, ensuring optimal growth and development of plants.

iv. Post-Harvest Storage: The IoT platform can be employed to monitor and regulate agricultural products during post-harvest storage in a cold chamber, thereby reducing spoilage and maintaining quality.
v. Poultry Farming: Many smallholder farmers in Nepal operate small-scale poultry farms. The IoT platform facilitates real-time remote monitoring of crucial parameters within the poultry farm, including temperature, humidity, and air quality. It can also automate feed and water systems, as well as heating, cooling, and lighting systems to optimize energy consumption.
vi. Farm Security and Access Control: Ensuring security and controlled access to a farmer's premises is of paramount importance. The IoT platform can be harnessed for this purpose, integrating sensors and actuators such as motion sensors and alarms. These elements provide early intrusion detection and facilitate prompt responses to safeguard the farm.

Incorporating the IoT platform into these agricultural contexts not only enhances the precision and efficiency of farming practices, but also empowers smallholder farmers in Nepal to achieve better yields, improved profitability, and enhanced security measures, ultimately contributing to the sustainable growth of their agricultural endeavors. In essence, this research not only identifies the unique demands and challenges faced by smallholder farmers in resource-constrained developing countries, but also offers a tangible solution in the form of a deployable, cost-efficient, and reliable IoT platform. By rigorously evaluating its features and performance, this study contributes to the advancement of agricultural technology, particularly in contexts where smallholder farmers play a pivotal role in sustaining local and national food production.

1.3 Motivation

Agriculture remains the backbone of Nepal's economy, contributing significantly to its GDP and providing livelihoods for a substantial portion of its population. Despite its critical importance, the sector faces numerous challenges that hinder its productivity and sustainability. Smallholder farmers, who manage a significant share of agricultural activities, encounter difficulties such as limited access to modern technology, inefficient traditional practices, and unpredictable climatic conditions. These challenges exacerbate food insecurity, economic instability, and rural poverty, prompting an urgent need for innovative solutions.

The motivation for this research stems from the recognition that the integration of IoT technology has the potential to address these challenges effectively. IoT offers a transformative approach to agriculture by providing real-time data and automation capabilities that can significantly enhance productivity and efficiency. For smallholder farmers in Nepal, who often work with limited resources and face substantial constraints, IoT presents a promising avenue for modernization without requiring large-scale investments. This research is driven by the need to bridge the gap between traditional farming practices and modern technological advancements. By designing a low-cost, reliable IoT platform tailored specifically for the needs of smallholder farmers, the aim is to empower these farmers with tools that enable precise monitoring and management of their agricultural activities. The platform's potential to improve real-time decision-making, optimize resource use, and enhance market access can lead to more sustainable and profitable farming practices.

Furthermore, addressing inefficiencies in current farming practices and developing practical solutions through case studies will provide valuable insights into how IoT can be effectively implemented. This research aims to contribute to the broader goal of achieving food security, economic resilience, and improved quality of life for smallholder farmers, thereby supporting Nepal's agricultural sector and aligning with global sustainability goals.

1.4 Objectives of the Research

1.4.1 Primary Objective:

- To design and implement a low-cost, reliable IoT platform specifically tailored for smallholder farmers in lower- and middle-income countries, with a focus on Nepal.

1.4.2 Specific Objectives:

I. To develop a cost-effective, customizable, scalable, and reliable IoT platform suited to the needs of smallholder farmers.
II. To enable farmers to monitor and control real-time sensor data related to crops, livestock, and other agricultural assets through web and mobile-based applications.
III. To demonstrate the platform's effectiveness through practical case studies, including polyhouses for off-season grafting of citrus fruits and cold chambers for post-harvest storage.
IV. To analyze and address the inefficiencies in traditional farming practices and the lack of suitable IoT solutions for smallholder farmers.

1.5 Significance and Scope of the Study

This thesis on "IoT-Based Agricultural Innovations: Cost-Effective Platforms for Smallholder Farmers in Nepal" holds significant implications for both academic understanding and practical applications. By focusing on the integration of IoT technology into agriculture, particularly within the context of smallholder farming in developing countries like Nepal, this research addresses critical gaps in current agricultural practices. It aims to enhance productivity, sustainability, and resilience in farming communities that are vital to food security and rural livelihoods. The findings from this study contribute to the academic discourse on IoT applications in agriculture and provide actionable insights for policymakers, researchers, and development practitioners seeking to promote technology-driven solutions in agriculture. The significance extends to other lower- and middle-income countries where smallholder farmers play a crucial role in the agricultural sector.

The scope of this thesis encompasses a focused exploration of IoT applications tailored specifically for smallholder farming communities in Nepal. It includes the design, development, and deployment of IoT-based systems for tasks such as real-time monitoring and control of environmental parameters like temperature, humidity, and soil moisture; crop management; irrigation control; pest detection; and post-harvest handling. The study aims to understand the socio-economic and technological factors influencing the adoption and effectiveness of IoT solutions in Nepalese agriculture. Geographically, it targets rural areas characterized by small-scale agricultural operations, focusing on key crops and livestock relevant to the region. Methodologically, the research employs interdisciplinary approaches to explore the intersection of agriculture, technology, and development studies, with an emphasis on participatory methodologies and stakeholder engagement for comprehensive insights into socio-technical systems.

1.6 Thesis Contribution:

This thesis contributes to the field of agricultural technology by focusing on the design and implementation of an IoT platform specifically tailored for smallholder farmers in Nepal. It addresses critical gaps in current agricultural practices by introducing innovative solutions that enhance productivity and sustainability. The research emphasizes practical applications, such as real-time monitoring of polyhouse microclimates and optimization of post-harvest storage, to improve agricultural outcomes in diverse geographic and climatic conditions prevalent in Nepal's hilly regions.

1.6.1 Key Contributions:

a) Design and Implementation of IoT Platform: Developed a customized web and mobile based IoT platform that integrates sensor technology for real-time monitoring and regulation of agricultural environments. This technological framework supports real-time monitoring and data management critical for smallholder farmers in Nepal, promoting efficient decision-making and resource management.
b) Enhanced Agricultural Monitoring and Control: By enabling real-time monitoring and control of crucial agricultural parameters such as soil moisture, temperature, and crop health through web and mobile applications, the platform provides a practical tool for farmers to optimize their farming practices. This capability improves decision-making and resource management, leading to increased productivity and efficiency.
c) Practical Case Studies and Validation: The thesis includes case studies that demonstrate the effectiveness of the IoT platform in real-world agricultural scenarios. These case studies, such as Polyhouse management for off-season grafting of citrus fruits and cold chamber monitoring for post-harvest storage, validate the platform's utility and impact, providing concrete evidence of its benefits.
d) Contribution to Academic and Practical Knowledge: Advanced theoretical understanding and practical applications of IoT in agriculture, contributing to sustainable rural development and food security initiatives in Nepal and similar emerging economies.

1.7 Organization of the Thesis:

This thesis is structured into five chapters, each contributing to a comprehensive understanding of the research topic.

Chapter 1 addresses the challenges prevalent in Nepalese agriculture, particularly among smallholder farmers. It articulates the need for tailored IoT solutions to address these challenges and establishes the research's significance. The chapter outlines the objectives, motivation, scope, and organization of the study, providing a roadmap for the subsequent chapters.

Chapter 2 reviews various aspects of IoT in agriculture. It covers IoT devices, sensors, actuators, processors, and their applications in agriculture. The chapter delves into IoT architecture, protocols, and connectivity solutions. It also discusses IoT adoption in agriculture, highlighting some global innovations and case studies demonstrating the transformative potential of IoT technologies in farming practices.

Chapter 3 describes the design and implementation of the IoT system platform and its features. It elaborates on the conceptualization of proposed IoT system architecture and the implementation. It covers the hardware setup, software development, and testing procedures. It also provides the possible inclusion of the platform in real-world use case scenarios.

Chapter 4 examines the IoT system's performance in real-world agricultural conditions. Through case studies and field trials in off-season grafting and pre- and post-harvest storage of citrus fruits, further, it offers empirical evidence of the system's effectiveness and potential benefits.

Chapter 5 summarizes the contributions of the research. It concludes by reaffirming the research's significance in advancing agricultural development in Nepal and underscores the importance of continued innovation and collaboration in harnessing the potential of IoT technology for the benefit of smallholder farmers.

1.8 Related Publications:

1.8.1 Journals

I. Lamsal, R.R.; Karthikeyan, P.; Otero, P.; Ariza, A. Design and Implementation of Internet of Things (IoT) Platform Targeted for Smallholder Farmers: From Nepal Perspective. Agriculture 2023, 13, 1900. https://doi.org/10.3390/agriculture13101900

II. Lamsal, R.R.; Acharya, U.K.; Karthikeyan, P.; Otero, P.; Ariza, A. Implementing Internet of Things for Real-Time Monitoring and Regulation of Off-Season Grafting and Post-Harvest Storage in Citrus Cultivation: A Case Study from the Hilly Regions of Nepal. AgriEngineering 2024, 6, 2082-2100. https://doi.org/10.3390/agriengineering6030122

III. Monitoring and Regulating Climatic Condition of Polyhouse for Successful Off-season Grafting of Citrus Fruits Using Internet of Things Platform. Int. J. Ag. Env. Biotech., 15(Special Issue):417-422. https://scholar.google.com/scholar?oi=bibs&cluster=3898062924253909198&btnI=1&hl=en

1.8.2 Conference

I. Invited Speaker presented a paper titled "Deployment of Internet of Things for Citrus Plant Grafting and Real-Time Internal Microclimate Regulation of the Storage House" in an international conference "Asian Citrus Congress-2023 (ACC-2023) held in Nagpur, India during 28th -30th October, 2023. https://accindia2023.iscindia.org.in/speaker.php

II. Participated and presented a paper titled "Monitoring and Regulating Climatic Condition of Polyhouse for Successful Off-season Grafting of Citrus Fruits Using Internet of Things Platform" in an international conference held at University of Agriculture science, Bangalore, India International Conference on "Advances in Agriculture and Food System Towards Sustainable Development Goals"(AAFS2022),22-24 August 2022

III. Presented a conference paper titled "Real Time Internal Microclimate Monitoring and Automation using IoT in Polyhouse for Growing Crops" at the Seventh International Conference IT4D 2021, held on 25-26 Nov 2021 in Kathmandu, Nepal.

Chapter 2: IoT Integration in Agriculture

Chapter 1 explored a detailed overview of Nepal's agricultural landscape and highlighted the critical role of smallholder farmers. It also discussed the potential opportunities and challenges associated with integrating IoT technology into agricultural practices. Furthermore, it outlined the motivations driving this study and defined its key objectives and contributions.

It provides a comprehensive overview of the IoT and its application in agriculture, laying the foundation for the research presented in this thesis. Beginning with the Introduction on IoT, the section 2.1 explores key backbone of IoT systems. Section 2.2 explores IoT architecture, followed by a discussion on IoT protocols in Section 2.3 and IoT connectivity in Section 2.4. Section 2.5 examines IoT platforms and their relevance in agriculture. Section 2.6 provides an overview of IoT sensors, actuators, processors, and edge devices used in agricultural applications. Section 2.7 addresses the applications, challenges, and future trends of IoT in agriculture. The Section 2.8 includes brief case studies on global IoT innovations in agriculture in and conclusion in Section 2.9.

2.1. Introduction to Internet of Things

The development of low-power, high-performance communication, processing, and networking integrated chips (ICs) has paved the way for many emerging technologies. IoT is one among these. IoT allows everyday objects to connect and exchange data over a network. It uses sensors, actuators, and various protocols for human-machine and machine-to-machine communication. This makes objects smart and capable of real-time data exchange and automation [16, 17]. An IoT system comprises sensor devices, actuators, and web and mobile applications. These components facilitate the monitoring, control, and display of real-time data. The platform provides the infrastructure to collect and process data from connected objects. This allows for efficient management and analysis, enhancing the functionality and intelligence of the IoT system. **Figure 2.1** depicts a typical IoT system. It includes the following elements:

IoT Devices: These are the sensors, actuators and processors that collect data and perform actions based on data received.

Communication Network: This is the medium through which the IoT devices send data to and receive commands from the IoT platform.

IoT Platform: This includes the server, web and mobile applications that process, display, and manage the data collected by the IoT devices. The platform often performs data analysis and decision-making to control the actuators.

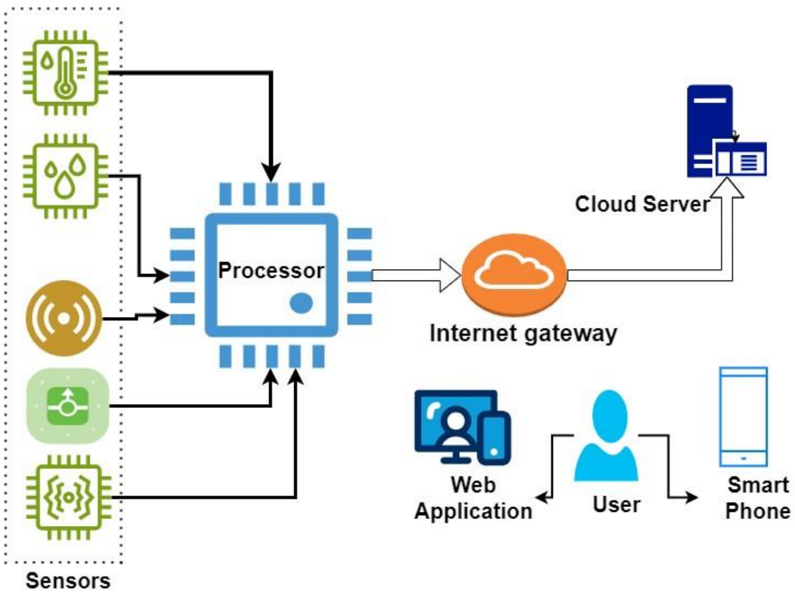

Figure 2.1 IoT System

2.1.1 Key IoT Application Areas

The IoT is transforming various fields with its applications. **Figure 2.2** depicts the use of IoT in diverse sectors. In agriculture, IoT provides farmers with real-time data about their farms, allowing them to manage resources more effectively and make informed decisions. This data-driven approach optimizes resource usage, increases crop yields, and reduces environmental impact. In healthcare, IoT devices like wearables monitor patients' vital signs remotely, improving care and early detection of health issues. IoT applications in manufacturing and industry include predictive maintenance, asset tracking, and automation. Smart homes use IoT to control lighting, heating, and security systems automatically, making living more convenient and energy-efficient. Smart cities employ IoT for better traffic management, waste collection, and public safety measures. In communication, IoT enables devices to connect and share data seamlessly, improving connectivity. Transportation systems benefit from IoT with improved fleet management and smart traffic control to reduce congestion. In retail, IoT improves inventory management, customer experience, and supply chain operations. Smart shelves, RFID tags, and connected devices provide real-time insights into product availability, customer preferences, and operational efficiency. In education, IoT supports interactive learning tools and helps manage school facilities more effectively.

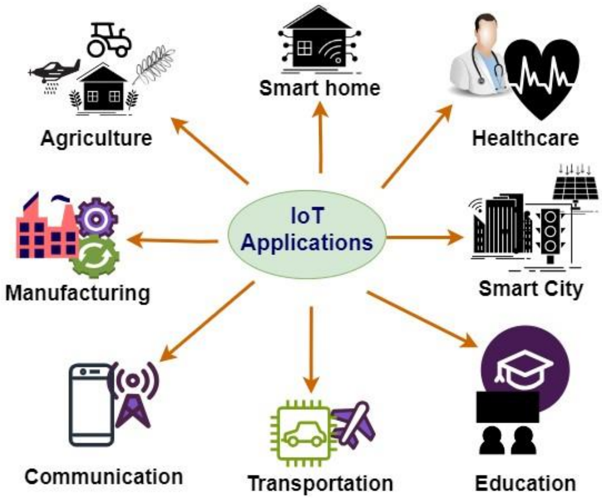

Figure 2.2 Key IoT Application Areas

2.2 IoT Architecture

The IoT architecture is the basic structure that helps IoT systems work smoothly. It includes different layers, parts, and connections that all work together. These layers help devices communicate to each other, process data, and perform tasks efficiently. With growing IoT awareness, the variety of IoT platforms has increased, leading to comprehension issues due to differing standards and approaches.

The basic IoT architectures can be structured in three, four, or five layers, each with distinct components and functions. **Figure 2.3** provides a visual representation of the layered architecture typical in IoT implementations. The most fundamental architecture in IoT is the three-layer architecture, which was developed during the early stages of IoT research [18, 19]. This Architecture comprises the perception layer, which includes sensors and actuators for data collection; the network layer, responsible for transmitting data to various devices and platforms; and the application layer, where data is processed and utilized for specific applications [20, 21].

The **four-layer architecture** adds the processing layer between the network and application layers, which involves data processing, storage, and analysis to enhance decision-making before the data reaches the application layer. The **five-layer architecture** further expands on this by introducing a business layer on top of the application layer. This layer manages the overall IoT system activities, services, and business models, ensuring the data processed is aligned with business objectives and strategies. It is essential for ensuring reliability, scalability, and quality of service (QoS) in contemporary applications. This architecture facilitates the efficient creation of applications and establishes connections among applications, users, and data [22]. Brief description of each layer is summarized below.

a) **Perception Layer**: This layer encompasses various sensors and actuators that collect and transmit data from the field. Key sensors include temperature and humidity sensors, soil moisture sensors, pH sensors, RFID, and cameras. Actuators such as exhaust fans, irrigation pumps, heaters, and relay drivers are activated based on predefined rules set by the sensor data. Data from these sensors are transmitted using protocols like RS232, I2C, Bluetooth, ZigBee, and Wi-Fi.
b) **Network Layer**: This layer is responsible for data transmission. It includes devices like routers and gateways that facilitate communication between sensors and servers. It uses communication networks like Wi-Fi, Bluetooth, cellular (3G/4G/5G), and Low-Power Wide-Area Networks (LPWAN) like LoRa and Sigfox.
c) **Processing Layer**: This layer includes servers or cloud platforms that store, analyze, and process the data received from the network layer. It often incorporates big data analytics, machine learning, and artificial intelligence capabilities to derive insights and make decisions. Protocols such as MQTT and CoAP are commonly used. Edge Computing Layer (Fog Computing): This layer processes data closer to where it is generated to reduce latency and bandwidth usage. It performs preliminary data processing and filtering before sending it to the cloud.
d) **Application Layer:** Focused on specific applications, this layer consists of mobile and web-based software applications that allow users to interact with the system, monitor data, and control devices. This layer delivers services like smart agriculture and smart home automation. It uses protocols like HTTP, CoAP, Rest API,and WebSockets for communication.
e) **Business Layer:** This layer manages the overall IoT system, including analytics and billing, ensuring that the system aligns with business objectives. It defines business models and strategies to ensure the IoT system meets organizational goals and provides value. Cloud platforms and ERP systems are widely used in this layer.

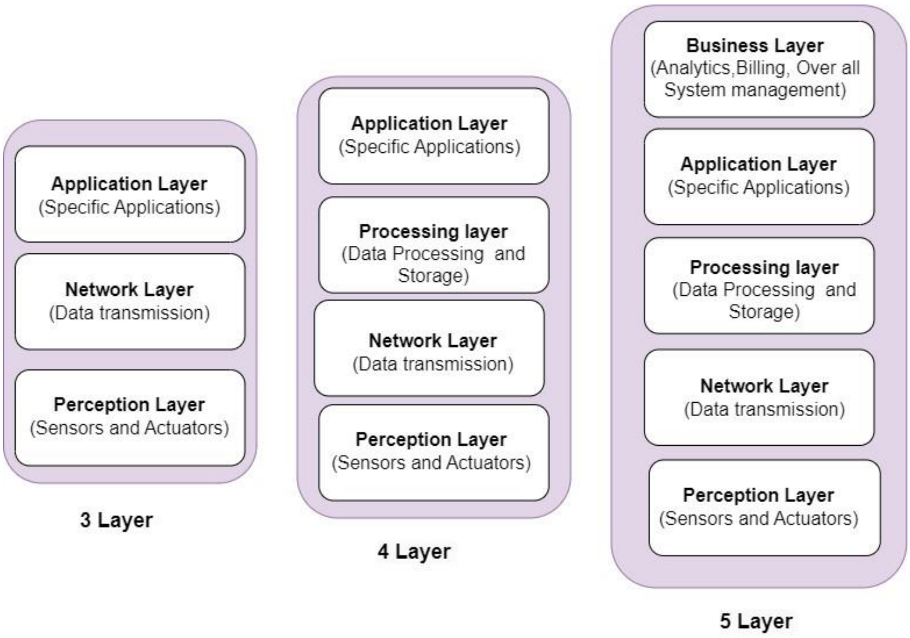

Figure 2.3 Layered IoT Architecture

A more comprehensive review of IoT architectures is presented in the following articles. In the Article [23] a reference IoT architecture is introduced, based on various state-of-the-art platforms. This reference architecture is compared with three open-source platforms (OpenMTC, FIWARE, SiteWhere) and one proprietary platform (Amazon Web Services IoT), demonstrating its usefulness in understanding, comparing, and evaluating different IoT solutions. The article [24] provides a comprehensive overview of key IoT elements, including architecture, data layer protocols, and data formats. It proposes a detailed reference IoT architecture, explains popular data layer protocols, and reviews common data formats for IoT systems. The importance of a gateway component for compatibility in real-world applications is highlighted. A survey of IoT platforms is presented, distinguishing between commercial and free/open-source platforms, with a detailed overview of the latter due to their heterogeneity. Additionally, the article includes an overview of relevant free and open-source software projects that can be used as building blocks for IoT systems and compiles a summary table of these platforms and projects. The article [25] defines an IoT architecture framework description that adheres to the international standard ISO/IEC/IEEE 42010:2011. This framework addresses concerns shared by IoT system stakeholders across various domains, such as transportation, healthcare, and Smart Grid. It provides a conceptual basis for understanding the notion of "things" in IoT and elaborates on shared concerns through a collection of architecture viewpoints, forming the core of the framework description.

2.3 IoT Protocols:

IoT protocols are the underlying communication frameworks that allow IoT devices to connect, exchange data, and interact with other systems. These protocols differ in terms of design, use cases, range, complexity, and resource requirements [26, 27, 28]. **Figure 2.4** shows some of the commonly used IoT protocols.

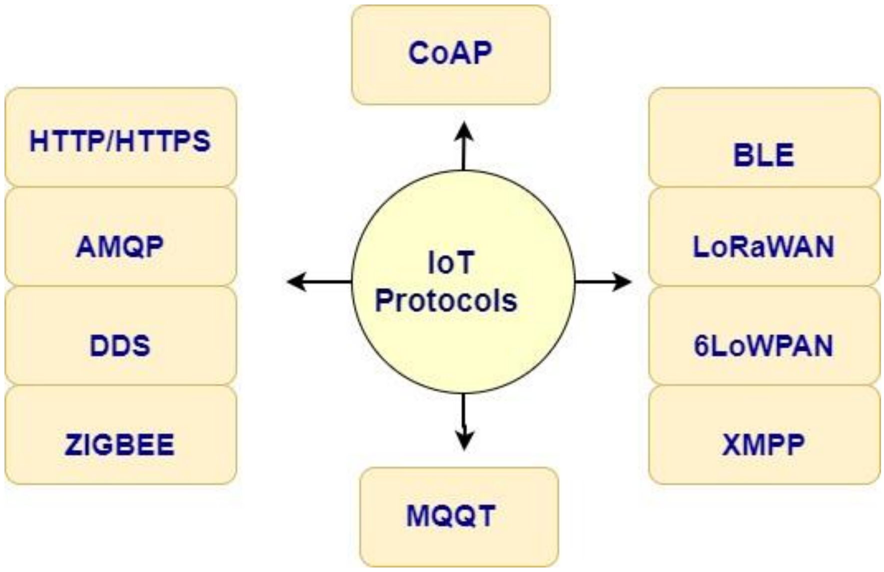

Figure 2.4 Commonly used IoT protocols

Protocols, like MQTT and CoAP, are lightweight and designed for resource-constrained environments, ideal for low-power devices and simple message exchange. Others, like HTTP/HTTPS, are more resource-intensive but offer broad compatibility and are well-suited for client-server communication. Protocols such as AMQP and DDS cater to more complex, enterprise-grade applications, providing reliable message queuing and real-time data distribution, respectively. For wireless communication, Zigbee and Bluetooth Low Energy (BLE) offer low-power options with varying range and suitability for different scenarios, while LoRaWAN provides long-range communication, making it suitable for remote monitoring and smart agriculture. Lastly, 6LoWPAN integrates IoT devices into existing IP networks by enabling IPv6 communication over low-power wireless connections. **Table 2.1** provides a summary of various IoT protocols, including their use cases, advantages, and disadvantages.

Overall, IoT protocols vary widely, and the choice among them depends on specific requirements such as power consumption, communication range, scalability, and security. Selecting the right protocol is crucial for building efficient, scalable, and secure IoT solutions.

Table 2.1 IoT Protocols Use Case, Advantages and Disadvantages

Protocols	Use case	Advantage	Disadvantage
MQQT	Ideal for low-bandwidth, high-latency networks, commonly used in IoT applications where devices need to send small messages frequently.	Lightweight, simple to implement, low bandwidth consumption, supports publish/subscribe pattern.	Lacks built-in encryption (usually used with TLS/SSL), less suitable for large-scale enterprise scenarios.

CoAP	Designed for resource-constrained IoT devices, useful for low-power applications and direct device-to-device communication.	Uses RESTful architecture (similar to HTTP), lightweight, suitable for low-power devices.	Less secure than other protocols, limited to small message sizes.
HTTP/HTTPS	Broadly used for client-server communication, ideal for web-based IoT applications and when compatibility with existing infrastructure is required.	Well-established, extensive support, compatible with most web technologies.	Higher overhead for smaller scale design, resource-intensive, not optimized for low-power devices.
AMQP	Designed for reliable, message-oriented communication, suitable for enterprise-grade IoT applications with high throughput and complex routing requirements.	Supports message queuing, routing, and reliable delivery, robust security features.	More complex, requires more resources, higher overhead than MQTT
DDS	Ideal for real-time applications and large-scale deployments where low latency and high throughput are critical.	Supports real-time communication, highly scalable, designed for distributed systems.	More complex, typically used in specialized applications, can be resource-intensive.
Zigbee	Suitable for wireless sensor networks, home automation, and industrial IoT applications where low-power wireless communication is needed.	Low power consumption, mesh networking, supports a large number of devices.	Limited range compared to other protocols like LoRaWAN, requires a coordinator for network management.
BLE	Commonly used in wearable technology, short-range IoT applications, and personal devices.	Low power consumption, widely supported, suitable for short-range communication.	Limited range, not designed for large-scale networks.
LoRaWAN	Ideal for long-range communication in IoT applications, suitable for remote monitoring and smart agriculture.	Long-range communication, low power consumption, supports a large number of devices.	Lower data transfer rates, limited in dense urban environments.
XMPP	Instant Messaging, Machine to Machine communication	Real time communication, long range, Considered reliable; features for message delivery and presence updates;	Overhead and complexity, scalability issue, limited adoption, may incur latency
6LoWPAN	Enables IPv6 communication over low-power wireless networks, useful for integrating IoT devices with existing IP-based systems.	IPv6 compatibility, low power consumption, supports mesh networking.	Requires additional infrastructure for routing, not as widely used as other protocols.

2.4 IoT Connectivity

IoT connectivity refers to the various methods and technologies that enable IoT devices to communicate and transmit data. It plays a critical role in ensuring that IoT systems function efficiently and reliably. Common connectivity options include wired connections like Ethernet and wireless connections such as cellular (3G/4G/5G), Wi-Fi, LPWAN (LoRa, Sigfox), Bluetooth, and Zigbee. Choosing the right connectivity option depends on several factors. These factors include range, data bandwidth, cost, and power consumption. However, there are challenges that must be considered to ensure optimal connectivity in IoT applications. These challenges include rural coverage, signal interference, and infrastructure limitations.

The **Table 2.2** provides a concise comparison of various IoT connectivity types, highlighting their key characteristics and common use cases. It shows how each connectivity type balances range, power consumption, data rate, cost, and reliability, guiding the selection based on specific IoT requirements.

Table 2.2 Comparison of various IoT connectivity

Connectivity Type	Range	Power Consumption	Data Rate	Cost	Reliability	Common Use Cases
Wi-Fi	Medium (up to 100m indoors)	High	High (up to 600 Mbps or more, depending on the standard)	Moderate to High	Generally reliable but prone to interference	Smart homes, industrial environments, high-data-rate applications
Bluetooth Low Energy (BLE)	Short (up to 30m)	Low	Moderate (up to 1 Mbps)	Low	Generally reliable	Wearables, short-range IoT applications, personal devices
Zigbee	Short to Medium (up to 100m)	Low	Low to Moderate (250 kbps)	Low	Generally reliable, supports mesh networking	Smart homes, building automation, sensor networks
LoRaWAN	Long (up to 15 km in rural areas)	Very Low	Low (0.3 kbps to 50 kbps)	Low to Moderate	Generally reliable, may be affected by urban interference	Remote monitoring, smart agriculture, low-bandwidth applications
Sigfox	Long (up to 10-15 km)	Very Low	Low (up to 100 bps)	Low to Moderate	Reliable for low-data-rate applications	Smart meters, remote sensing, low-bandwidth applications

NB-IoT	Long (similar to cellular networks)	Moderate to Low	Low to Moderate (up to 250 kbps)	Moderate	Highly reliable, uses cellular infrastructure	IoT applications requiring wide coverage, moderate data rates
LTE-M	Long (similar to cellular networks)	Moderate	Moderate to High (up to 1 Mbps)	Moderate	Highly reliable, uses existing cellular networks	Asset tracking, mobile applications, moderate to high data rate applications
6LoWPAN	Short to Medium (similar to Zigbee)	Low	Moderate	Moderate	Generally reliable, supports mesh networking	IoT devices with IPv6 compatibility, mesh networks

2.5 IoT Platforms:

IoT platforms are a crucial component of the IoT ecosystem, providing the tools and infrastructure to manage connected devices, process data, and create applications. Their versatility and scalability make them integral to the success of IoT projects across a wide range of applications, enabling innovative solutions and driving digital transformation. There are various types of IoT platforms, each with distinct advantages. Cloud-based platforms, such as AWS IoT [29], Microsoft Azure IoT [30], and Google Cloud IoT [31], offer scalability and flexibility, making them suitable for large-scale IoT deployments and providing easy access to computing resources. Edge-based platforms process data closer to the source, reducing latency and improving response times, which is essential for real-time processing needs. Hybrid platforms combine both cloud-based and edge-based approaches, balancing scalability with low-latency processing for optimal performance.

2.5.1 Core Functions of IoT Platforms

The essential core functions of IoT includes:

i. Device Management: IoT platforms allow for the setup, monitoring and managing of IoT devices. They ensure devices are connected securely and can be remotely managed.
ii. Data Collection and Storage: These platforms collect data from connected devices and store it for analysis. Data can come from sensors, actuators, cameras, or other IoT devices.

iii. Data Processing and Analytics: IoT platforms often include tools for processing, analyzing, and visualizing data. This can involve real-time analytics, machine learning, and artificial intelligence to derive insights and make predictions.

iv. Connectivity and Communication: IoT platforms support various connectivity protocols, enabling seamless communication between devices and with the cloud. They often support Wi-Fi, Bluetooth, cellular, and low-power wide-area networks (LPWANs).

v. Application Development and Integration: Many IoT platforms offer development tools and APIs (Application Programming Interfaces) to create custom applications or integrate with other software systems. This flexibility allows for tailored IoT solutions.

vi. Security and Compliance: IoT platforms prioritize security, implementing encryption, authentication, and other security measures to protect data and ensure compliance with regulations.

2.5.2 IoT Cloud platforms for Agriculture

These platforms vary in their approach to IoT in agriculture. Some, like AWS IoT and Azure IoT, offer comprehensive suites with deep integration across their respective cloud ecosystems, providing a high degree of flexibility and scalability. Others, like ThingSpeak [32], focus more on data visualization and are suitable for smaller-scale projects. While all these platforms support IoT device management, data collection, and analytics, the level of industry-specific capabilities differs. Platforms like Google Cloud IoT (retired in Aug,2023) and IBM Watson IoT [33] offer advanced AI and machine learning features, while others focus on simplicity and ease of integration with common IoT protocols. Cloud-based IoT platforms are critical in modern agriculture, providing the infrastructure, tools, and services to connect, monitor, and analyze data from IoT devices. These platforms vary in terms of features, scalability, analytics, integration, and industry-specific capabilities. **Table 2.3** summarizes the comparison of various cloud-based IoT platforms that can be used in the agriculture context:

Table 2.3 Comparison of various IoT connectivity

Platform	Key Features	Communication Protocols	Integration	Use Case
Microsoft Azure IoT Hub	Device management, bi-directional communication, security features,	MQTT, HTTPS, AMQP, IoT Hub Device SDK	Azure services	General IoT solutions; used in precision agriculture for monitoring and controlling farming operations.
AWS IoT Core	Fully managed service, device management, supports analytics, storage, and machine learning.	MQTT, HTTP, WebSocket	AWS services	Analytics, storage, machine learning; used for real-time monitoring, predictive analytics, and automation in agriculture.

IBM Watson IoT	Device management, data analytics, integration with IBM Cloud for AI and machine learning.	MQTT, HTTPS	IBM Cloud services	AI and machine learning; applied in agriculture for predictive analytics, crop health monitoring, and automated irrigation.
ThingSpeak	Data collection, analysis, and visualization, often used for smaller projects and education.	HTTP, MQTT	MATLAB integration	Smaller-scale projects, education; used for data logging and basic analysis in agricultural research and educational projects.
Particle	Hardware, connectivity, cloud services, device management, data storage, third-party integrations.	HTTP, MQTT	Third-party services	Comprehensive IoT solutions; used for connected sensors and devices in precision farming and agricultural automation.
Losant	Device management, data visualization, workflow automation, scalable from prototypes to large deployments.	MQTT, HTTP	Third-party services	Enterprise IoT solutions; used in large-scale agricultural operations for data visualization and process automation.
Cisco IoT Control Center	Connectivity management, device onboarding, connectivity analytics, global connectivity across network types.	MQTT, HTTP, CoAP	Cisco IoT, Integration with various network providers	Connectivity management; used to manage connectivity for large networks of agricultural IoT devices.
Bosch IoT Suite	Device management, data management, analytics, supports a wide range of industries.	MQTT, HTTP, CoAP	Integration with Bosch services and solutions	Wide range of industries; used for various agricultural applications including field monitoring and equipment management.

2.6 Overview of IoT Sensors, Actuators, Processors and Edge Devices in Agriculture

2.6.1 Sensors

In agricultural IoT, different sensors are used to track and control environmental conditions, which helps to improve productivity and sustainability. Soil moisture sensors like the ECH2O EC-5 [34] and Teros 12 [35] measure the volumetric water content in soil, enabling precise irrigation management to ensure optimal hydration for crops. Temperature and humidity sensors, such as the DHT11, DHT22 (AM2302), and SHT31, provide critical data on ambient conditions, allowing farmers to adjust practices and maintain ideal growing environments [36], [37]. Light sensors, including the TSL2561 and BH1750 [38], measure sunlight or artificial light levels, ensuring crops receive the necessary light intensity for photosynthesis and optimal growth.

For monitoring soil and water pH levels, sensors like the Atlas Scientific EZO-pH [39] and Bluelab pH Pen [40] offer accurate and reliable measurements, crucial for maintaining appropriate acidity or alkalinity for different crops. Nutrient sensors, such as the Yara N-Sensor [41], detect essential nutrient concentrations in the soil, aiding in informed fertilization decisions to enhance crop health and yields. CO2 sensors, including the MH-Z19[42] and COZIR-A [43], measure carbon dioxide levels, particularly useful in controlled environments like greenhouses to improve plant growth through optimized photosynthesis rates.

Integrated weather stations, like the Davis Instruments Vantage Pro2 [44] and Ambient Weather WS-2902[45], combine multiple sensors to provide comprehensive weather data, including temperature, humidity, rainfall, wind speed, and direction. This holistic weather information empowers farmers to make informed decisions regarding planting, irrigation, and pest control, mitigating risks associated with adverse weather conditions. These commercially available sensors collectively enable precise monitoring and management of various environmental factors, significantly advancing the field of agricultural IoT.

2.6.2 Actuators

In the context of agricultural IoT systems, various actuators are essential for implementing automated responses based on sensor data, optimizing farming practices, and enhancing efficiency. Automated irrigation systems, such as sprinkler valves and drip irrigation actuators, ensure precise water delivery based on real-time soil moisture data, conserving water while maintaining adequate crop hydration. Climate control systems, including smart thermostats like the Nest Thermostat and automated ventilation systems, help regulate temperature and humidity in greenhouses, creating optimal growing conditions. Lighting control systems, such as the Philips GreenPower LED grow lights and smart light switches, provide adjustable light spectra and automated schedules to enhance photosynthesis and energy efficiency.

Fertilizer dispensers, like automated fertigation systems and variable rate dispensers, deliver nutrients directly to plant roots and apply fertilizers at varying rates across different field sections, optimizing nutrient distribution and reducing waste. Automated pest control systems, including IoT-enabled smart traps like Trapview and ultrasonic pest repellers like PestChaser, monitor and manage pest populations, minimizing the need for chemical interventions. Automated harvesting systems, such as the Agrobot E-Series robotic harvesters and mechanical pickers, use IoT data to determine the optimal harvesting time and perform the task with precision, reducing labor costs and improving efficiency.

Additionally, automated feeding systems for livestock, like the MooMonitor+ smart feeders and automated water dispensers, ensure precise feeding schedules and adequate hydration based on real-time health and consumption data. These IoT actuators enable automated, data-driven interventions in agriculture, enhancing productivity, resource efficiency, and sustainability by creating a more responsive and optimized farming environment.

2.6.3 Processors and Edge Devices in Agriculture

In agricultural IoT systems, processors and edge devices are essential for collecting and processing data from various sensors, enabling real-time decision-making and automation. The Arduino Uno, a popular microcontroller board, is known for its ease of use and low cost, making it ideal for simple data collection and control tasks in basic IoT projects. Similarly, the ESP8266 offers a low-cost Wi-Fi microchip with full TCP/IP stack and microcontroller capability, suitable for wireless connectivity and basic processing power. For more complex data processing tasks, the Raspberry Pi stands out as a small, affordable single-board computer that supports a full operating system.

Industrial-grade processors like the Intel Edison and NVIDIA Jetson Nano provide advanced capabilities for more demanding agricultural applications. The Intel Edison supports complex computational tasks, including image processing and machine learning, while the NVIDIA Jetson Nano excels in edge AI applications, such as image recognition and predictive analytics. The EdgeX Foundry platform offers an open-source edge computing solution that ensures interoperability between different IoT devices and services, facilitating scalable and flexible IoT solutions for real-time data processing. Devices like the Cisco Fog Computing Gateway enable data processing closer to the source, reducing the need for constant cloud connectivity and improving response times, which is particularly beneficial in remote agricultural settings. The Google Coral Dev Board and Azure IoT Edge combine edge computing with AI, enabling on-device machine learning inference and real-time data analysis, which are crucial for intelligent decision-making in agriculture. Additionally, low-power wide-area network (LPWAN) technologies such as LoRaWAN and NB-IoT allow for long-range communication with low power consumption, making them ideal for connecting remote sensors and edge devices over large agricultural fields. Together, these processors and edge devices enable efficient data collection, processing, and decision-making, optimizing various aspects of farming and enhancing productivity and sustainability.

2.7 IoT in Agriculture: Applications, Challenges, and Future Trends

IoT is transforming agriculture through precision farming techniques like soil monitoring and weather prediction, optimizing irrigation systems, and enabling smart irrigation for efficient water management. Livestock monitoring with IoT devices improves animal health and productivity, while farm automation using automated machinery and drones increases operational efficiency. The benefits of IoT in agriculture include increased efficiency, cost savings, sustainability, and improved crop yields. However, challenges such as data security, cost and accessibility, technical complexity, and skills gaps remain. Looking ahead, emerging IoT trends and innovations, integration with AI, and the expansion of IoT applications promise to further enhance and revolutionize the agricultural sector [46]. Some of the most notable trends and innovations in IoT for agriculture includes:

2.7.1 Precision Agriculture

Real-Time Monitoring**:** Sensors embedded in the soil, plants, or farming equipment collect data on soil moisture, temperature, pH levels, and other critical parameters. This data allows farmers to make informed decisions about irrigation, fertilization, and crop management, enhancing yield and resource efficiency.

Drones and Aerial Imaging: Drones equipped with cameras and sensors provide detailed aerial images and data on crop health and field conditions. This technology allows for precise application of water, pesticides, and fertilizers, reducing waste and environmental impact.

2.7.2 Smart Irrigation Systems

Automated Water Management: IoT-based irrigation systems use soil moisture sensors and weather data to automate watering schedules. These systems optimize water usage, reducing waste and promoting sustainability.

Cloud-Based Control: Farmers can control irrigation systems remotely through mobile apps or web-based dashboards, allowing for real-time adjustments and monitoring.

2.7.3 Livestock Monitoring and Management

Wearable IoT Devices for Livestock: Wearable devices track livestock health, behavior, and location, providing early detection of illness and improving herd management. These devices can also monitor reproductive cycles, aiding in breeding programs.

Automated Feeding Systems: IoT-driven feeding systems automatically dispense food based on livestock requirements, ensuring proper nutrition and reducing waste.

2.7.4 Farm Automation and Robotics

Autonomous Vehicles and Machinery: IoT-enabled autonomous tractors, harvesters, and other machinery can perform tasks like plowing, planting, and harvesting with minimal human intervention. These technologies improve efficiency and reduce labor costs.

Robotic Automation: Robots designed for specific tasks, such as weeding or fruit picking, are increasingly being integrated into farming operations.

2.7.5 Supply Chain and Traceability

IoT for Supply Chain Management: IoT devices track agricultural products from farm to market, enhancing supply chain visibility and reducing food spoilage. RFID tags and sensors can monitor temperature, humidity, and other conditions during transport, ensuring product quality.

Blockchain Integration: Combining IoT with blockchain technology allows for secure and transparent tracking of agricultural products, improving traceability and consumer confidence.

2.7.6 Data Analytics and Artificial Intelligence (AI)

Advanced Data Analysis: IoT generates vast amounts of data, which can be analyzed using AI and machine learning algorithms to identify trends and predict outcomes. This analysis helps farmers optimize resource usage, improve yields, and reduce costs.

Predictive Analytics for Agriculture: AI-based predictive analytics can forecast weather patterns, crop yields, and pest outbreaks, allowing farmers to plan accordingly.

2.7.7 Vertical and Urban Farming

IoT in Vertical Farming: IoT technology is used to control environmental conditions in vertical farming setups, providing optimal growth conditions for crops. This trend is especially relevant in urban areas where space is limited.

Smart Urban Farms: IoT enables the creation of urban farms with automated systems for watering, lighting, and nutrient management, contributing to local food production and sustainability.

These trends and innovations in IoT for agriculture reflect a growing emphasis on precision, automation, and sustainability. By integrating advanced technologies like AI, robotics, and blockchain, IoT is transforming traditional farming methods and opening new possibilities for food production and agricultural management. The adoption of these trends is expected to continue, leading to increased efficiency, reduced resource waste, and a more sustainable approach to agriculture.

2.8 Brief Case Studies on Global IoT Innovations in Agriculture

The integration of IoT technologies in agriculture has led to significant advancements across various regions. In Israel, Netafim's [47] IoT-based precision irrigation has enhanced water use efficiency and crop yields while reducing water consumption. In India, Stellapps [48] utilizes IoT for dairy management, allowing for real-time monitoring of milk production and quality, which minimizes spoilage and boosts milk output. Similarly, Farmsio[49] Technologies in India and the UK employs IoT-based farm management to improve decision-making for smallholder farmers, reducing unnecessary pesticide use and increasing yields. In Kenya, Twiga Foods [50] has used IoT-based market connections to link smallholder farmers with markets, effectively decreasing post-harvest losses and improving income. Aerobotics[51] in South Africa leverages drone-based IoT monitoring for early detection of crop diseases and pests, which reduces crop loss and minimizes chemical use. Brazil's Agrosmart [52] applies IoT for precision agriculture to enhance irrigation and fertilization, leading to better yields and reduced resource use. Australia's Ceres Tag [53] employs smart tags for livestock management, enabling remote monitoring of cattle, which reduces theft and improves grazing management. In the USA, Bushelfarm [54] (formerly FarmLogs) offers IoT-enabled farm management for remote monitoring, optimizing operations and reducing over-irrigation. Plantix [55], operating in Germany and India, utilizes AI-based IoT for plant disease diagnosis, promoting early disease detection and sustainable practices. Additionally, Farm from a Box [56] in the USA provides IoT-enabled modular farming systems that support sustainable agriculture in developing regions. Lastly, Norway's Yara International [57] applies IoT for nutrient management, optimizing nutrient application and enhancing crop yields. In Nigeria, Hello Tractor [58] uses IoT technology to connect small-scale farmers with tractor owners, allowing farmers to book tractor services and enabling owners to monitor their equipment's location and usage in real time. **Table 2.4** offers a concise overview of innovative IoT-based agricultural services implemented in various countries, detailing the country, provider, technology, application, and impact.

Table 2.4 Global IoT application in Agriculture

Country	Provider	Technology	Application	Impact
Israel	Netafim [47]	IoT-based Precision Irrigation	Smart irrigation	Improves water use efficiency, increases crop yields, and reduces water consumption.
India	Stellapps [48]	IoT for Dairy Management	Dairy farm monitoring	Enhances milk quality, reduces spoilage, and increases overall milk production.
India/UK	Farmsio Technologies [49]	IoT-based Farm Management	Smart farming	Improves decision-making for smallholder farmers, reduces unnecessary pesticide use, and increases yields.
Kenya	Twiga Foods [50]	IoT-based Market Connection	Market access	Connects smallholder farmers with markets, reduces post-harvest losses, and improves income.
South Africa	Aerobotics [51]	Drone-based IoT Monitoring	Crop health monitoring	Facilitates early detection of diseases and pests, reduces crop loss, and minimizes chemical use.
Brazil	Agrosmart [52]	IoT for Precision Agriculture	Smart farming	Improves irrigation and fertilization, leading to better yields and reduced resource use.
Australia	Ceres Tag [53]	Smart Tags for Livestock Management	Livestock tracking	Enhances remote cattle monitoring, reduces cattle theft, and improves grazing management.

USA	Bushelfarm (Formerly FarmLogs) [54]	IoT-enabled Farm Management	Farm monitoring	Optimizes farm operations and reduces over-irrigation through remote monitoring.
Germany /India	Plantix [55]	AI-based IoT Plant Disease Diagnosis	Crop health management	Facilitates early diagnosis of plant diseases using AI, reduces crop loss, and promotes sustainable practices.
USA	Farm from a Box [56]	IoT-enabled Modular Farming System	Sustainable farming	Promotes sustainable farming in urban and rural regions with modular agricultural systems using IoT.
Norway	Yara International [57]	IoT for Nutrient Management	Nutrient optimization	Enhances crop yields and reduces waste through precision nutrient application.
Nigeria	Hello Tractor [58]	IoT based tractor Tracking and Booking services	Location tracking and usage	Improves access to mechanization for Nigerian farmers, increases productivity, and reduces manual labor.

2.9 Conclusion:

In this section of the thesis, we explored the domain of the IoT and its fundamental aspects, applications, architecture, connectivity properties, and platforms. This understanding sets the stage for appreciating the transformative impact of IoT, especially in agriculture. An IoT system integrates sensors, devices, networks, and data processing capabilities to enable seamless communication and data exchange. The core components include sensors that capture real-time data, connectivity solutions that transmit this data, and data analytics platforms that derive actionable insights. The ultimate goal is to enhance operational efficiency and enable autonomous decision-making. IoT's versatility spans various sectors such as agriculture, healthcare, industry, Smart homes, and smart cities etc. Each application demonstrates IoT's ability to revolutionize traditional processes with enhanced intelligence and efficiency.

IoT architecture typically includes the perception layer, network layer, and application layer. This modular design ensures scalability, flexibility, and interoperability, adapting to diverse requirements. IoT platforms like AWS IoT, Microsoft Azure IoT, and Google Cloud IoT provide the necessary infrastructure for device management, data collection, and integration. Effective IoT connectivity is essential for seamless data transmission. IoT devices use Wi-Fi, Bluetooth, ZigBee, LoRaWAN, and cellular networks, each suitable for different use cases. Reliable connectivity is crucial for the real-time performance of IoT systems. The integration of IoT with cloud platforms enhances its capabilities. IoT cloud platforms offer scalable storage, powerful data analytics, and machine learning, facilitating informed decision-making and ensuring data security.

The agricultural sector benefits immensely from IoT innovations. Precision agriculture uses IoT to monitor soil moisture, temperature, and crop health, optimizing irrigation, fertilization, and pest control. Automated systems reduce labor and improve efficiency. IoT also enhances supply chain management, reducing post-harvest losses. Global case studies highlight IoT's impact in agriculture. These examples show IoT's potential to address agricultural challenges and promote sustainable practices.

This exploration of IoT fundamentals, applications, architecture, platforms, and cloud integration underscores its transformative potential. IoT in agriculture, supported by case studies, highlights its ability to revolutionize farming, enhance productivity, and ensure sustainability. As IoT evolves, its impact will drive innovation and efficiency across sectors, creating a smarter, connected world.

Chapter 3: IoT Platform Targeted for Smallholder Farmers

In the previous chapter, we explored the foundational aspects of the IoT, covering its architecture, protocols, connectivity options, and transformative applications across diverse sectors. We also discussed critical components like IoT platforms and cloud integration, emphasizing their role in scalability and effective data management. Specifically, our focus on IoT's potential in agriculture underscored its capacity to revolutionize farming practices, enhance productivity, and foster sustainability, laying a solid foundation for further examination in this and upcoming chapters.

This part of the thesis is based on the author's published article [59]. It is focused on developing IoT platforms suitable for smallholder farmers. It begins with the introduction section followed by related works in section 3.2. The methodology section 3.3 highlights the key requirements. In the Section 3.4 overall description and design of the proposed customized IoT system architecture is explained. This section also includes hardware and application components, reliability and performance monitoring. The chapter concludes with result, discussions and conclusion.

3.1 Introduction

The adoption of IoT technology in agriculture presents a transformative opportunity for smallholder farmers, who form the backbone of food production in many developing countries [60]. However, the successful implementation of IoT solutions for these farmers necessitates careful consideration of their unique needs and constraints. Nepal, a lower-middle-income country in South Asia, predominantly features smallholder farming communities operating on modest land holdings. These smallholders often adhere to traditional farming methods, relying on familial labor, which has become increasingly inefficient in contemporary agricultural landscapes [61,62]. To enhance their productivity and efficiency, smallholder farmers require affordable and accessible IoT-based systems. However, the prevailing IoT solutions in the market primarily cater to large-scale commercial enterprises, rendering them unsuitable for the specific needs and constraints faced by smallholder farmers. In response to this gap, we have introduced a cost-effective, customizable, scalable, and dependable IoT platform tailored expressly for smallholder farmers. This platform empowers them to visualize, monitor, and control real-time data pertaining to their crops, livestock, and other agricultural assets.

3.2 Related Work

Doshi et al. developed a smart farming prototype using a third-party cloud application that connects various agriculture sensors and displays sensor data on the farmer's smartphone [63]. Ayaz et al., in their article, highlighted the potential use and challenges of wireless sensors and IoT in agriculture. Authors have also analyzed the IoT devices and communication techniques associated with agriculture applications [64]. Nigussie et al. propose an "IoT-based irrigation management for smallholder farmers in rural sub-Saharan Africa" and found that an IoT-based irrigation management system can significantly improve the efficiency and effectiveness of irrigation for smallholder farmers in rural sub-Saharan Africa. The study conducted in Ethiopia showed that the system was able to reduce water use by 60% while maintaining or increasing crop yields. The design provided farmers with real-time information on soil moisture levels and weather conditions, allowing them to make informed decisions about when and how much to irrigate [65]. Dahane et al. present low-cost smart farming for enhancing the irrigation efficiency of smallholder farmers. The study conducted in Algeria showed that the system using low-cost sensors and a mobile application provided real-time data and feedback to farmers, reducing water consumption by up to 50% while maintaining or increasing crop yields. The authors suggest that IoT-based smart farming systems can significantly enhance irrigation efficiency but require careful attention to affordability, accessibility, local context, and collaboration between stakeholders [66]. Bayih et al. describe a case study in Ethiopia where an IoT and wireless sensor network (WSN)-based system was implemented for smallholder farmers to monitor and control their irrigation and fertilization practices. The system used low-cost sensors and a web-based platform to provide real-time data and feedback to farmers. The study found that the system could significantly improve crop yields, reduce water usage, and increase fertilizer efficiency while reducing labor costs and minimizing environmental impact [67].

Maraveas et al. review studies on IoT-based greenhouse monitoring and control systems which use sensors and actuators to collect and adjust environmental factors. These systems can improve crop growth and quality, energy efficiency, and resource management. The authors suggest that these systems can enhance the sustainability and profitability of greenhouse agriculture, but implementation requires careful attention to issues such as affordability, reliability, scalability, and collaboration between stakeholders [68]. Lufyagila et al. discuss using an IoT-powered system to monitor environmental conditions in a poultry house in Tanzania. The study deployed a low-cost system with sensors to monitor temperature, humidity, and air quality and a cloud-based data storage and analysis platform. The results showed that the system effectively improved animal health and productivity, was user friendly and accessible, and highlighted the importance of sustainable technologies in developing countries agricultural sectors [69]. Quayson et al. introduce a framework for technology for good social foundations in sustainable supply chains, emphasizing the importance of a supportive environment for smallholder farmers, including access to technology, training, and market incentives. The research highlights the potential for technology-based interventions to improve social and environmental outcomes and calls for future research to ensure inclusivity for smallholder farmers in developing countries [70]. Cheng et al. present a study on the development and implementation of an intelligent agriculture system that utilizes IoT technology in Taiwan. The system includes environmental monitoring sensors and a cloud-based data analysis platform. The study results showed that the system improved crop yields and resource management while being user friendly and accessible. The researchers suggest that the system has the potential to improve sustainability and profitability in agriculture by reducing resource use and increasing productivity. Further system development could include automated irrigation and fertilization [71].

Oliveira-Jr et al. discuss a case study on developing and deploying an IoT-based sensing platform for e-Agriculture in Mozambique. The platform included environmental monitoring sensors and a cloud-based data analysis platform. The study showed that the platform was effective in improving crop yields and resource management and being user friendly and accessible. The researchers suggest that the platform could be further developed to include weather forecasting and crop disease management, which could reduce crop losses. The study highlights the potential of IoT technology for e-Agriculture in Africa and provides insights for future research and development in other regions and for other crops [72]. Sekaran et al. developed a smart agricultural management system using IoT. This method gathers agriculture data from sensors from the fields. It creates results for ranchers, is essential for observing harvest development, and diminishes their time and energy. The information gathered from the field is stored in the cloud and field control is achieved by using IoT gadgets. The idea introduced in the paper could expand the efficiency of the harvests by decreasing the wastage of assets used in agribusiness fields [73]. Agricultural IoT solutions can help the sector improve operational efficiency, save costs, minimize waste, and enhance product quality.

Haque et al. developed secure IoT devices for the smart agriculture system. Smart agriculture based on the IoT is a system that uses sensors to monitor irrigation activities and automate crop production in the agricultural field. Farmers may monitor the state of their land from any location [74]. Bera et al. presented an intelligent precession Agriculture, where drones can be used to collect the sensor data and send to a ground server station. The data are secured using block chain-based authentication [75].

Jiang et al. described the deep learning approaches for apple fruit detection in agriculture. Deep learning, which demonstrates its ability in fruit handling and grouping, is utilized to arrange apples. The profound neural organization with various convolution layers and individual neurons is analyzed and assessed [76]. Bu et al. introduced a smart IoT agriculture system with deep learning reinforcement integrated in the cloud server for smart decisions, like how much water is required for the better growth of the crop [77]. Parvathi et al. proposed an intelligent agriculture management system to improve agricultural benefits and crop production. The goal is to use IoT and automate the task. It is intended to perform weeding, water system, detecting mugginess, endeavoring to alarm birds and animals, keeping up with reconnaissance, and so forth, to control the geolocation of gadgets from a distance [78]. Katanga et al. proposed an IoT-based, cost-effective hardware solution using voice-activated technology, centered around the ESP8266 NodeMCU micro-controller. It enables home automation via voice commands through Google Assistant and IFTTT integration and offers agricultural monitoring with soil moisture, temperature, and humidity analysis. The system efficiently manages water flow based on soil conditions and utilizes Wi-Fi for data transfer to cloud storage (Thingspeak) and the Blynk IoT platform [79, 80].

Most of the work mentioned above has been concentrated on applications that either use more complicated systems or depend on third-party applications unsuitable for smallholder farmers. Smallholder farmers in low- and middle-income countries face multiple challenges in adopting the existing IoT architecture, including high costs, inadequate infrastructure, technical complexity, limited customization, and difficulties in maintenance and support. Consequently, a more affordable, user friendly, and customized IoT solution is required to cater to their unique needs and boost their productivity and livelihoods.

3.3 Methodology

The methodology for design and implementation of IoT system in agriculture for smallholder farmers involves several key steps:

a) Comprehensive Literature Review: First, we review existing IoT applications in agriculture, focusing on how they can be used by smallholder farmers. We look at the challenges and opportunities of using IoT in this context.
b) Design of the IoT Architecture: We design an IoT system specifically for smallholder farmers, considering their limited resources and technical skills. We ensure the system is localized, customizable, reliable, affordable, and scalable.
c) Data Collection, Analysis, and Field Testing: We use IoT sensors in the field to collect data. This data is analyzed to see if the IoT system meets our research goals. We test

the system both in research stations and with actual smallholder farmers to ensure it is effective, reliable, and easy to use.

d) Evaluation of the Architecture: Finally, we evaluate the IoT system based on its reliability, cost, and ease of use for smallholder farmers. We compare it with existing solutions to see how well it performs.

3.3.1 Key Requirements

During the design of the IoT system architecture, several key requirements for smallholder farmers were identified as below:

a) Low Cost and Availability: The IoT devices and sensors should be affordable and readily available in the local market to ensure smallholder farmers can purchase and use them.
b) Reliable Connectivity: The system should have reliable and robust connectivity options, such as wireless and cellular networks, to ensure real-time data transmission and reception.
c) Data Management: The platform should be capable of collecting, storing, and analyzing data from IoT devices and presenting it in an easy-to-use format for farmers.
d) Scalability: The platform should be scalable and adaptable to meet the evolving needs of smallholder farmers and their communities.
e) User-Friendly Interface: The platform should have an intuitive and easy-to-use interface, allowing farmers to operate it without extensive technical knowledge.
f) Security: The system should implement strong security measures to protect data and devices, ensuring the privacy of the farmers.
g) Localization: The platform should use locally available hardware and software and address the specific needs and conditions of smallholder farmers in the target region.
h) Community Engagement: The system should empower farmers by involving them in its design and operation, providing training, and offering relevant information to improve their livelihoods.
i) Data Visualization: The platform should offer tools like dashboards and visualizations to help farmers easily access and interpret data for making informed decisions about their farming practices.

3.4. Description of the Proposed Customized IoT Architecture and Platform

The custom IoT platform is designed to meet the unique needs of smallholder farmers involved in various types of farming. This platform is designed to accommodate a wide range of requirements within a single IoT framework. Key features include user-friendly interfaces, simple deployment procedures, brief training sessions for easy operation, and accessible local maintenance and support services to encourage widespread adoption. The proposed IoT architecture for smallholder agriculture incorporates a sensor network, edge computing, and cloud computing to collect and process field data. The architecture is designed to be low cost and user friendly, enabling smallholder farmers to access it with limited resources. Additionally, it is scalable to meet the changing needs of farmers. **Figure 3.1** illustrates the customized IoT platform approach for smart agriculture.

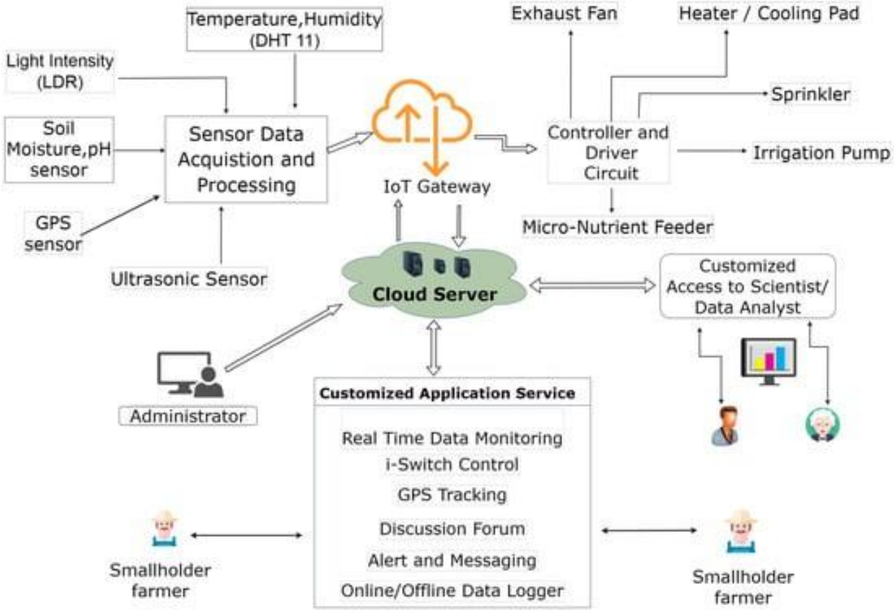

Figure 3.1 Proposed customized IoT platform

The proposed IoT system stands out for its customization capabilities, allowing users to select application services tailored to their specific needs. This flexibility extends to sensor and switch services, where users have the freedom to configure their system as per their preferences. For instance, one user might opt for three sensors and two switch services, while another may require two or three switch-based services. Furthermore, the architectural framework incorporates a discussion forum, serving as a valuable platform where experts can address general user inquiries and offer remote support and guidance.

3.4.1 Overview of User Application and Services

The user-centric application and service structure of the proposed system can be summarized as follows:

a. Role-Based Access: Administrators play a pivotal role by creating distinct roles for end users, including smallholder farmers, Custom users, scientists, and data analysts.
b. Device Deployment: End users possess the capability to set up IoT sensor devices and controllers within their agricultural fields, ensuring seamless integration with their operations.
c. Data Management: Data generated by diverse IoT sensors undergo meticulous collection, processing, and transmission to a cloud server. This data repository is accessible to data analysts, experts, and scientists who can offer valuable insights and feedback.

d. Customized Service Applications: End users leverage customized service applications, empowering them with the tools needed for real-time monitoring and control of their systems.

3.4.2 Key Features within the Proposed System:

The architectural design of the proposed system focuses on key features important for smallholder farmers. These features include:

i. Real-time Data Monitoring and Visualization: Farmers can access and act on real-time sensor data, allowing them to visually monitor field conditions at set intervals. They can track various agricultural parameters like temperature, humidity, light intensity, pH levels, tank water levels, soil moisture, and more.
ii. I-Switch Control: The "i-Switch" application lets farmers remotely activate electrical and electronic devices through custom web and mobile applications. This is useful for greenhouses, polyhouses, and irrigation fields, where automation is crucial. I-Switch helps regulate internal microclimates by controlling exhaust fans, fogging systems, heating, and cooling to maintain desired conditions.
iii. GPS Tracking: This feature tracks agricultural logistics and machinery using GPS sensors. The data is sent to the cloud and displayed on browsers and mobile apps, providing real-time visibility of agricultural assets.
iv. Alerts and Messaging: Users receive alerts and messages via email and SMS when events surpass predefined thresholds. This keeps farmers informed about their agricultural operations.
v. Data Logging and Analytics: Sensor data is logged and stored in cloud-based databases and local storage. Farmers can export data to local computers, and analysts and researchers can access this data for in-depth analysis and feedback. The stored data is easily retrievable for customized analysis.
vi. Discussion Forum: A dedicated forum allows smallholder farmers to connect and communicate with peers, research scientists, data analysts, and other stakeholders. This helps in sharing and acquiring important information through text and image-based queries and suggestions.
vii. Onsite and Online Data Logging Architecture: To address unreliable internet connections, the system combines onsite and online data logging. This ensures data is available on local storage devices with timestamps, even without a stable internet connection. **Figure 3.2** shows the Onsite and online data log architecture.

Figure 3.2 Onsite and online data log architecture

3.4.3. Hardware and Application Design Components

The proposed system incorporates various components to create an IoT architecture that can collect, analyze, and act on data from the smallholder. These components include a microcontroller unit, sensors, actuators, a gateway, network connectivity, data storage, a cloud platform, and a mobile/web application.

The proposed architecture uses a low-cost, low-power, open-source microcontroller unit nodemcu esp8266 with a Wi-Fi module embedded in it. It consists of 17 general purpose input output pins. It supports digital and analog I/O with 11 pins and 1 pin, respectively. In addition to this, there are pins to support UART, I2C, and SPI interface. The wireless network connectivity has the ability to create its own network, a maximum clock speed of 160 MHz with 128 KB of RAM, and 4MB flash memory, which are good choices for the proposed system design. The gateway serves as the device that connects the sensors and actuators to the internet. The proposed architecture is based on Wi-Fi and mobile cellular network connectivity. The network topology is a star topology, where all the sensor nodes are connected to the central Wi-Fi router. This topology is more suitable for the proposed system as the smallholder farmers usually require 3–5 sensors and actuators in response to our research question. The range of Wi-Fi is 100 m in line of sight and if required can be extended by using another nodemcu as a relay module. To improve signal reliability and prevent interference, the NodeMCU can be integrated into a PCB.

Sensors such as temperature, humidity, soil moisture, light, pH, and Global Positioning System (GPS) can be integrated into the architecture to collect environmental data. Actuators like motors, valves, or relays can control various aspects of the smallholder's operation, such as irrigation or climate control systems. Data collected by the sensors are stored locally in a microSD card and sent to the cloud for reliable data storage. After comparing various cloud services and their associated cost and features, Microsoft Azure is chosen as the cloud platform to host the application and cloud storage. Both a web server-based application and android-based mobile application are developed to access the IoT platform. The reason for choosing Microsoft Azure cloud services is due to its cost effectiveness and scalability.

Similarly, many local smallholder farmers use android-powered devices to access the internet. The proposed architecture provides services in both web-based applications as well as in mobile applications. Time-series data visualization and a graphical dashboard interface are integrated for analytics and visualization. All these components integrate together to enable the smallholder to make data-driven decisions about managing their operation. The client-side hardware set-up is depicted in **Figure 3.3**

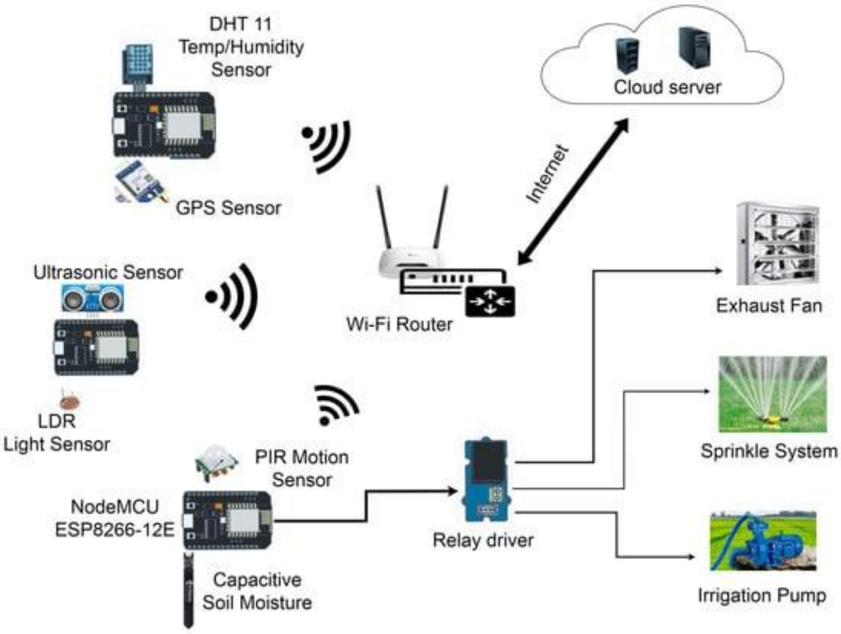

Figure 3.3 Client-side IoT devices

3.4.4 Platform Application Design:

Our system application has been thoughtfully designed to cater to both web and mobile platforms, using a robust client-server-based architecture. Within this framework, every user is allocated a personalized dashboard, granting them immediate access to real-time monitoring and control capabilities. Furthermore, users have the flexibility to extract time-series data for in-depth data analytics.

User-Centric Architecture:

The architectural blueprint of our user registration system application is visually represented in **Figure 3.4**, providing a comprehensive overview of how user interaction and data flow are seamlessly integrated.

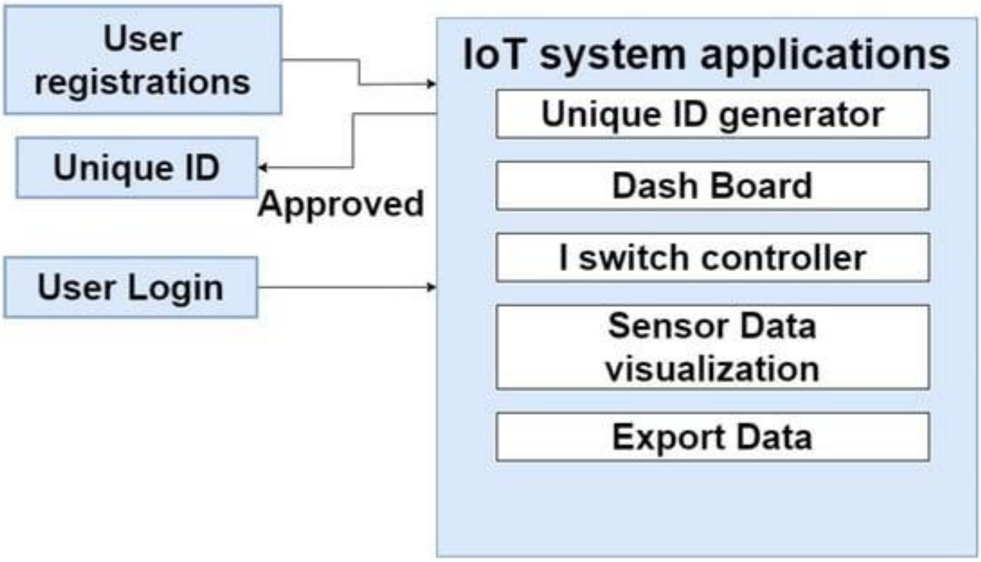

Figure 3.4 User registration and system application architecture

3.4.5 Multi-Platform Application and User Interface

Our system application works smoothly on both web and mobile platforms using a strong client-server architecture. Each user gets a custom dashboard for real-time viewing, monitoring, and controlling their application. Users can also export time-series data for detailed analysis.

The implementation of our IoT system happens in two phases: user registration and system application.

User Registration: User profiles are created, and IoT devices and sensors are set up based on their specific needs.

System Application: Users are guided to their personalized applications, allowing them to monitor real-time data, take actions, and perform data analysis.

Dynamic Data Visualization: Data visualization is shown in different forms in the following figures. For example, **Figure 3.5** displays the web application dashboard. This dashboard gives users a complete view of three key sensor parameters: temperature, humidity, and water level. It also allows users to control a switch connected to the water pump.

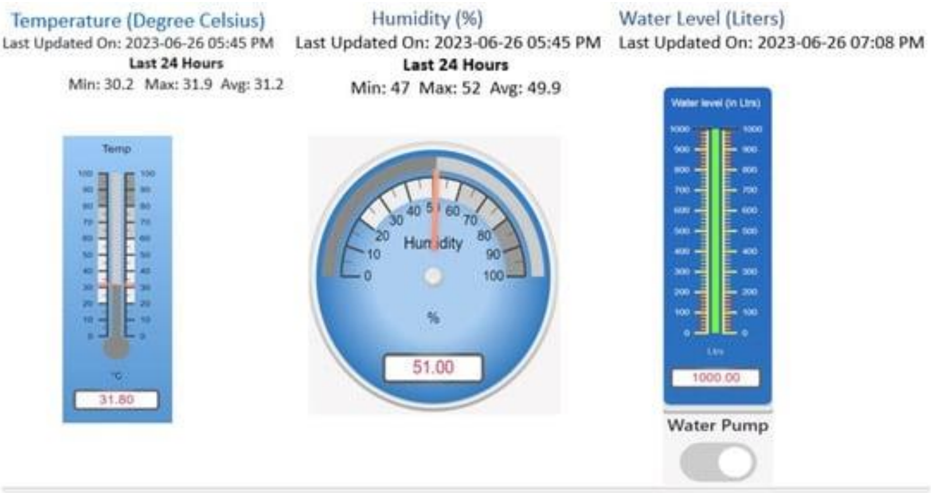

Figure 3.5 Web application and dashboard

Figure 3.6 shows the mobile application dashboard, allowing users to access important data and control functions easily on their mobile devices. **Figure 3.7** and **Table 3.1** present the visualization of time-series data and the data export template. This helps users export stored data at various intervals, such as hourly, weekly, monthly, or within specific date ranges.

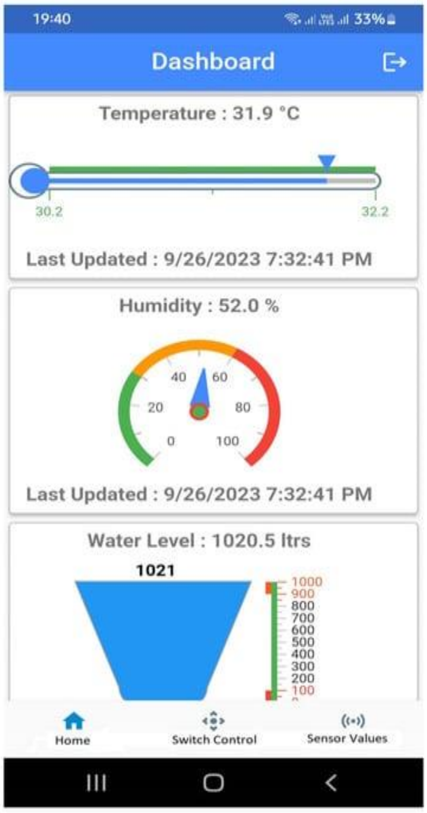

Figure 3.6 Mobile application dashboard

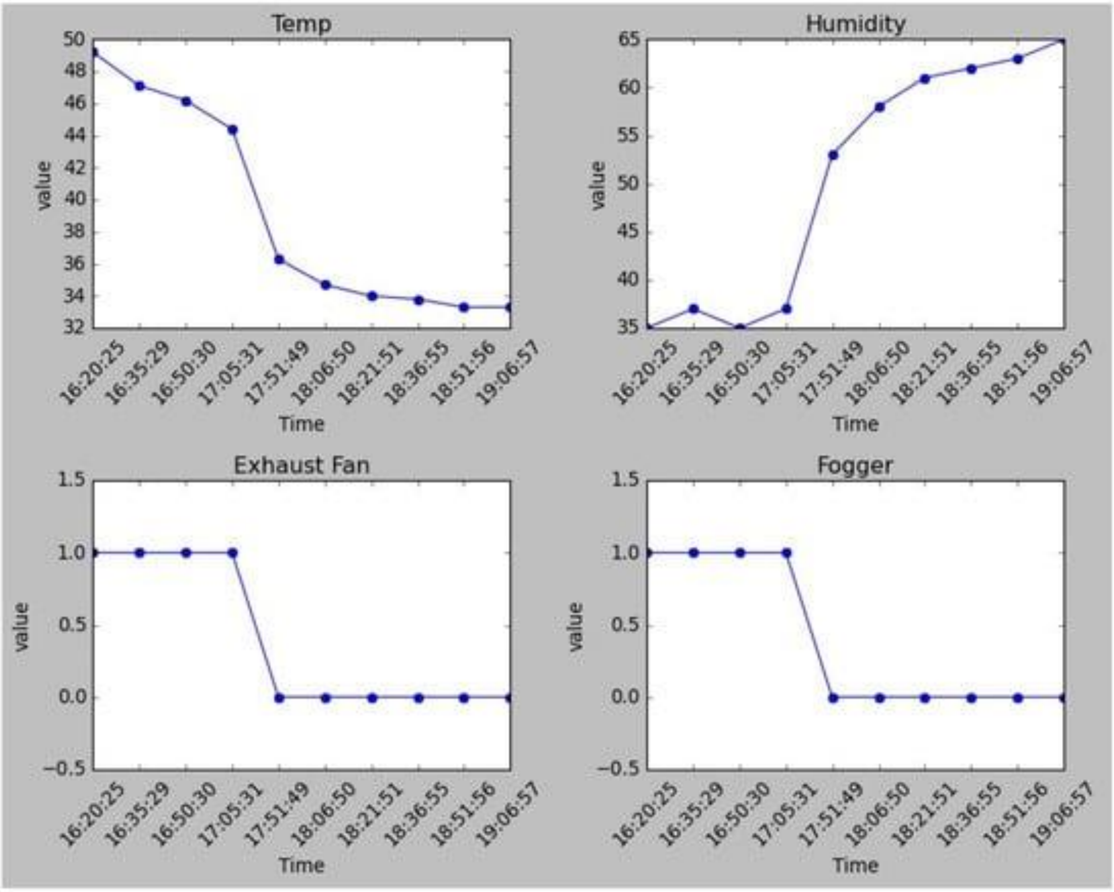

Figure 3.7 Time-series data visualization

Table 3.1 Data export template in csv format

Device-Id	Temp	Humidity	Exhaust Fan	Fogger	Updated On
GAG0000035	49.2	35	1	1	6 November 2023 16:20
GAG0000035	47.1	37	1	1	6 November 2023 16:35
GAG0000035	46.2	35	1	1	6 November 2023 16:50
GAG0000035	44.4	37	1	1	6 November 2023 17:05
GAG0000035	36.3	53	0	0	6 November 2023 17:51
GAG0000035	34.7	58	0	0	6 November 2023 18:06
GAG0000035	34	61	0	0	6 November 2023 18:21
GAG0000035	33.8	62	0	0	6 November 2023 18:36
GAG0000035	33.3	63	0	0	6 November 2023 18:51
GAG0000035	33.3	65	0	0	6 November 2023 19:06

3.5. Reliability and Performance Monitoring

After developing the proposed architecture and system design, various custom application services were tested to evaluate their performance and reliability. To simulate real-world scenarios, users were created and assigned custom application services that are frequently required. Additionally, IoT devices were configured and installed by the users. The application services, update interval, and observed period are summarized in **Table 3.2**. Analysis of the observation data revealed that the system remained highly reliable throughout the observed period.

Table 3.2 Reliability and performance monitoring

User	Application Service	Update Interval	Observation Period	Remarks
1	Temp, Humidity	15 min	120 days	System found to post data at regular interval reliably.
2	Water Tank level (Ultra-sonic sensor based)	7 min	120 days	Success (one or two false triggering due to improper isolation later rectified).
3	i-Switch Control Water Pump, Fogger, Garden Light, Exhaust Fan	Every sec	90 days	Server latency of 1 s observed sometimes (due to low bandwidth server).
4	Temp/Humidity Online/Offline Data logger	10 min	120 days	Data posted in the cloud and Logged in the microSD card at the given interval.
5	Passive IR-Motion Sensor	Every sec	90 days	Detects and posts the data.
6	Light intensity (Darkness Level) (0–1024)	Every 15 min	120 days	Detects and post the data as per the schedule.

This work shows the design and implementation of an IoT platform to improve agricultural operations for smallholder farmers in Nepal. Currently, the use of IoT in agriculture in Nepal is lacking. The proposed IoT architecture provides smallholder farmers with real-time data, enhancing the efficiency and productivity of their farms. This study serves as a model for other smallholder farmers and sheds light on the challenges and opportunities of implementing IoT in smallholder agriculture. It highlights the platform's affordability, reliability, scalability, data management, ease of use, and localization benefits. These findings are crucial for developing future IoT-based agricultural systems tailored to the needs of smallholder farmers in Nepal and similar areas. Our developed system is hosted on the website Medhayantra , www.medhayantra.com (accessed on 07 July 2024) and is accessible to everyone. **Figure 3.8** shows some of the implementation sites.

Figure 3.8 Implementation site: National Citrus Research Program, Dhankuta, Nepal

Figure depicts the experimental set-up for offseason grafting of Citrus fruits inside a polyhouse. The proposed IoT platform is used to regulate internal microclimate in real time.

3.6 Results Discussion

The performance and comparison section below highlights the proposed system's important features, services, and performance. The cost analysis is performed for the proposed method based on the number of users and upgrade plan. The data storage analysis and server load test are performed to determine parameters like data file size, sample size, throughput, and response time. During this average observation period of 339 days a total of 817,633 messages were stored in the cloud by different devices. This provides an average of messages per day = 817,633/339, which is rounded to 2412 messages/day. The total storage file size recorded is 14,238.28 kB. Considering the Cloud server with a capacity of 20 GB, the capacity can be extended to 20 GB/14,238.28 kB about 1473 times. This indicates that, if one user is allocated 50 MB of storage, approximately 400 users can be accommodated. The server load test is performed to find the throughput for 120 users over the interval. The server load test is conducted using an Apache J meter version 5.5. The subsequent Section 3.6.1 to 3.6.3 discuss the server load test, and the performance comparison with the Blynk IoT platform and ThingSpeak platform and cost analysis, respectively. Based on the number of sensor data send to the server the file size

3.6.1. Server Load Test

We have conducted the server load test to check the performance of our system using Apache JMeter version 5.5 software. Table 3.3 shows the server load test for different numbers of users for the various parameters: response time, throughput, and the network sent and received. Overall, the load test results demonstrate that increasing the number of users leads to higher server load, longer response times, and reduced network traffic. **Figure 3.9** shows the server load test data for the different numbers of users.

Table 3.3 Server load test data for different number of users

Number of Users	Number of Samples	Response Time (ms)	Throughput (Transactions/s)	Network-Received (kB/s)	Network - Sent (kB/s)
10	1482	804.6	12.29	19.75	2.78
30	1684	1979.64	14.21	22.83	3.22
50	19,912	2614.73	12.88	20.68	2.92
100	7653	6054.77	11.11	17.72	2.52

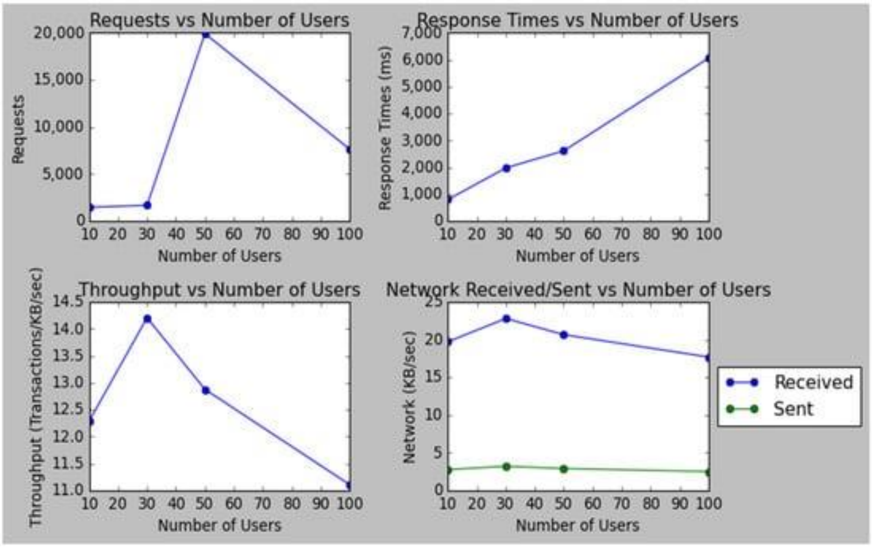

Figure 3.9 Server load test data for the different number of users

The system's data export function allows users to download data from the cloud to their local device. Seven devices were deployed to calculate the cloud storage and file size of the sensor data over time. Each device logged sensor data to the cloud at regular intervals. The stored data are downloaded to the local machine. **Table 3.4** represents the number of transactions, messages, and file size.

Table 3.4 Number of transactions, messages, and file size

S. No.	Number of Transaction	Sensor Parameters	Number of Messages	File Size (kB)	No. of Days	Interval (Minute)	Average Message /Day
1	6022	2	12,044	370	125	15	96
2	7696	4	30,784	483	156	15	197
3	14,640	2	29,280	872	386	15	76
4	29,772	3	89,316	1936	225	10	397
5	42,959	2	85,918	2560	390	10	220
6	49,967	3	149,901	3216	465	10	322

3.6.2. Performance Comparisons

We have taken two similar IoT platforms, Blynk [81] and Thingspeak [82], for comparative analysis. The comparative chart for the existing platforms, the proposed system features, and plans are shown **Figure 3.10**. The features of the proposed system are listed in **Table 3.5**.

Table 3.5 Proposed IoT platform features and parameters

Features	Parameter
Level of complexity	Easy
Web APP + Mobile App	Includes both Web and mobile application
Data stream	11 message/second
Data storage	Cloud and also onsite field storage sd card
Image support	Image support for web application
Ease of maintenance and support	Easy and User centric
API integrated	REST API
Security	Unique Id + Cloud security
Alert feature	Email/SMS
Scalability	Architecture is designed for scalability
Data export (csv)	1 year/Unlimited (on-site field storage)
Price	NPR 5270 (USD 39.9)

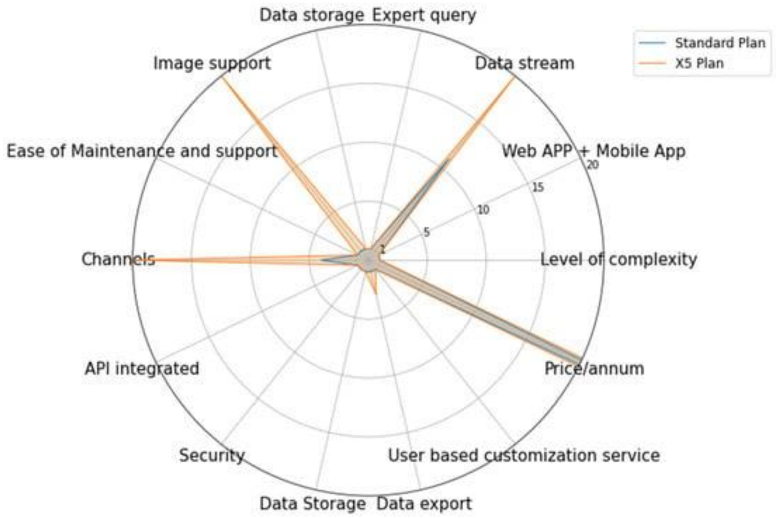

Figure 3.10 Performance comparison of the proposed system with a different plan

Figure 3.10 shows the performance comparison of the proposed system with different plans. For scalability and performance enhancement, the X5 plan is included, which support more users with enhanced features. The cost analysis for the X5 plan is derived based on the fact that the architecture is scalable; hence, the only change is to upgrade the cloud service instance from A0 to A2. The A2 instance has 2 processor cores with 3.5 GB RAM and 490 GB storage in contrast to the A0 instance, which runs in 1 processor core, 0.75 GB RAM, and 20 GB storage.

The Blynk Plan offers medium complexity with support for applications, widgets, and some data streaming capabilities. The ThingSpeak Plan is geared towards more complex projects with better scalability, advanced technical support, and data export options. The proposed system has a lower level of complexity but offers a range of features, including web and mobile app support, data storage, security, and customization options.

3.6.3. Cost Analysis

The proposed IoT platform is hosted in Azure A0 instance to experiment. The pricing and parameters of Azure instances, which could be potential use for scalability for our platform, are shown in **Table 3.6**.

Table 3.6 Pricing and Parameters of Azure instances

Our Hosting Cloud Platform				
Instance	Core	RAM (GB)	Temp Storage (GB)	Cost/Month (USD)
A0	1	0.75	20	14.6
A1	1	1.75	225	71.5
A2	2	3.5	490	143.2
A1v2	1	2	10	51.1

We have incorporated the essential features in our platform required for smallholder farmers' applications. In addition to proposing an IoT system, we have conducted a cost analysis for its deployment based on the number of users who can utilize the shared platform. The associated costs, calculated using contemporary local pricing, are listed in **Table 3.7**. The number of users share the variable application development cost.

Table 3.7 Cost analysis based on local market (in Nepali Rupees NPR *)

Number of Shared User	Custom IoT Device and Hardware Cost ** (One Time)	Connectivity Cost/Annum	Cloud cost/Annum	Application Development Cost/User (One time)	Support and Update/Annum
10	3500	1000	1500	20,000	10,000
30	3300	600	800	10,000	4000
50	3000	500	600	8000	3000
80	3000	450	500	6000	2500
100	3000	450	500	5000	2000

** Cost breakdown of custom IoT devices in NPR at local market: Esp8266 Nodemcu = 400, Power supply unit = 150, DHT 11 sensor = 200, Ultrasonic sensor = 200, PIR Motion Sensor = 150, 10 Amp relay module = 100, Wi-Fi router = 2000, connectors and accessories = 300. The slight reduction in cost for more users is to reflect on bulk purchase. * 132.165311 NPR = 1 USD (22 March 2023, 09:55 UTC)

The cost/user per annum is calculated as Cloud service cost + Connectivity cost + Application development cost + Support and update cost = NPR (Nepali Rupees) 4000 + NPR 450 + NPR 2321 + NPR 2000 = NPR 8771 (USD 272.73). The average cost is estimated as the total application Development cost/Number of users, i.e., 1,880,000/270, approx. 6963, further spread over 36 months and results in NPR (Nepali Rupees) 193.4 per user. Considering the number of users as 100, the total estimated cost per user per annum for average service remains Cloud service cost + Connectivity cost + Application development cost + Support and update cost = NPR 500 + NPR 450 + NPR 2320 + NPR 2000 = NPR 5270 (USD 39.9).

Based on Figure 3.11, it can be observed that the cost of deploying IoT systems significantly decreases as the number of users increases. This reduction in cost makes it affordable for smallholder farmers to invest in such systems, enabling them to manage their farms effectively. The reliability and durability of the system are observed by deploying the IoT device using this platform. The comparative cost analysis for 100 users is tabulated in **Table 3.8**. It is found that the proposed system cost indicates approximately 5 times and 18 times less compared to the Blynk and thing Speak platform.

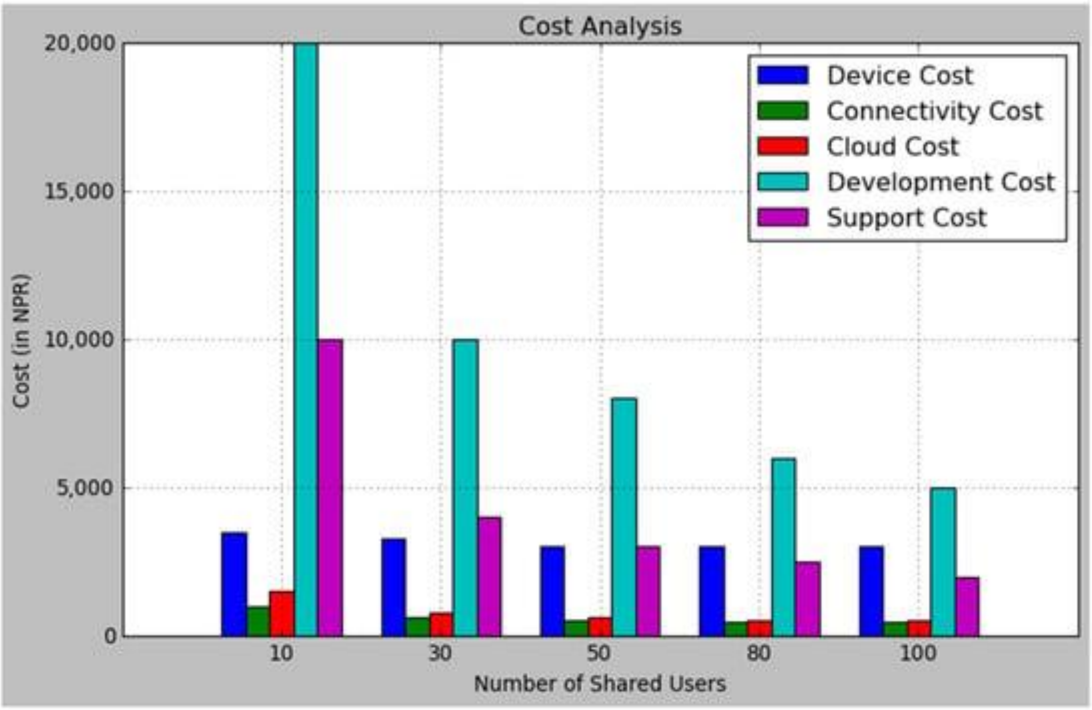

Figure 3.11 Number of users and cost of deployment

Table 3.8 Comparative cost/annum with existing system

Blynk IoT Platform	
Plan	Plus
Cost/Annum	$159
Things Speak Platform	
Plan	Standard
Cost/Annum	$710
Proposed System	
Plan	Standard
Cost/Annum	$39

3.7 Limitations of the Study

The limitations of this study include the limited sample size. The study is conducted on a limited number of users, and the results may not be generalizable to all smallholder farmers. Another limitation is the cost of the proposed solution for a very limited service application that may be a barrier for some smallholder farmers to adopt the solution.

3.8 Conclusions

This research aimed to identify the specific needs to design and implement an IoT platform in agriculture specifically tailored to the needs and resources of smallholder farmers of lower and middle incoming countries like Nepal. The proposed IoT architecture includes a combination of sensor networks, edge computing, and cloud computing and is designed to be low cost and easy to use. The research included a literature review, design of the IoT architecture, data collection, data analysis, and field testing. The developed system features and performances are evaluated with the existing system and found to be low cost, has inclusive features, and is reliable. Moreover, the proposed platform incorporates an offline data logging system in situations when internet connectivity is lost, which is an additional feature compared to the existing systems. In an observation for an average period of 339 days a total of 817,633 sensor messages are stored in the cloud server which accounts for, on average, 2512 messages/day. The storage file size recorded for this period is 14,238.28 KB. We are using Azure Version 2022-11-02 as a cloud server. With the basic plan (A0 Instance), which has a storage of 20 GB, we can accommodate 400 users if one user is allotted 50 MB of data, which is adequate for the smallholder farmers operation for more than a year. The data can be download from the server and can be analyzed for future reference. Furthermore, the proposed system was implemented to regulate the internal microclimate for offseason grafting of citrus fruit Acid-Lime (sunkagati-1) inside a polyhouse. The grafting success of 84 percent was achieved, which is near to the regular on-season grafting rate. The real-life implementation of the platform is now deployed and hosted at www.medhayantra.com. The implementation and results showed that the proposed IoT architecture is reliable and effective in providing smallholder farmers with real-time data and control to improve the efficiency and productivity of their agricultural operations. However, there are also challenges to its implementation, such as the willingness of the smallholder farmers to adopt the technology, community training and support, and further reduction in cost and technical capacity for proper operation.

Chapter 4: Realtime Monitoring and Regulation

The previous chapter highlighted various design aspects of IoT systems suited to smallholder and community farmers. The content of this section is based on our published article [83] which focuses on the practical application and evaluation of IoT technology in citrus farming in Nepal, specifically addressing off-season grafting and post-harvest storage. It begins with an introduction to the significance of citrus farming and its challenges. The remaining section is organized as follows. Section 4.2 discuss the related work and Section 4.3 presents the proposed system and methodology. We have discussed the experimental analysis, results and discussion in Section 4.4 and section 4.5 followed by the limitation. Finally, in section 4.6 we have discussed the main conclusions of our research work and possible future lines of research.

4.1 Introduction

Citrus fruit, mainly mandarin orange cultivation in Nepal's hilly regions, has been a source of economic prosperity and sustainability for many farmers. The geoclimatic conditions in these areas are highly suitable for farming, with approximately 62 out of 77 districts actively involved in citrus production [84,85]. The demand for grafted saplings has been steadily rising, and both smallholder and commercial farmers are drawn to the profitability of local mandarin orange cultivation [86]. However, several pressing challenges have hindered the sector's growth and sustainability, necessitating innovative solutions.

4.1.1 Citrus Cultivation and Post-Harvest Storage in Nepal

The hilly areas of Nepal exhibit a varied topography, ranging from subtropical to temperate zones, with altitudes fluctuating between 800 to 3,000 meters above sea level [87]. One of the key factors contributing to Nepal's suitability for citrus fruit cultivation in hilly regions (800-1600 m) is the favorable temperature range. The hilly terrains experience moderate temperatures throughout the year, with warm summers and cool winters. This temperate climate is well-suited for the growth and development of citrus trees, as they thrive in temperatures ranging from 15 to 30 degrees Celsius [88]. The ample sunlight in the hilly areas of Nepal further enhances the citrus cultivation prospects. Citrus fruits require a significant amount of sunlight for photosynthesis and fruit maturation. The sloping landscapes of the hills ensure that citrus orchards receive optimal sunlight exposure, contributing to robust and healthy fruit production. Additionally, the well-drained soils in the hilly regions are conducive to citrus cultivation. Citrus trees prefer soils with good drainage to prevent waterlogging, and the diverse range of soils in Nepal's hilly areas, including loamy and sandy soils, provides suitable options for citrus cultivation. As the number of orange orchards continues to flourish, the peak of production often results in a surplus supply, leading farmers to face the challenge of selling their oranges at reduced prices. An effective alternative to this predicament is the implementation of proper orange storage techniques. By successfully storing oranges for 60 to 90 days, farmers can take advantage of a substantial price increase, nearly tripling their earnings. A recent study in regions with cold storage facilities showed that farmers experienced considerable benefits from this approach [89]. Thus, having a reliable and efficient storage method is of paramount importance for the prosperity of farmers, offering them a strategic advantage in the market.

4.1.2. Economic Significance

The citrus sector significantly enhances the income and food security of rural communities, with most districts actively engaged in citrus production. Citrus cultivation holds significant economic importance in Nepal, contributing to the country's agricultural sector and overall economic well-being. Citrus cultivation serves as a source of income generation for numerous farmers across Nepal, especially in the hilly regions where the conditions are favorable. The cultivation of citrus fruits, such as oranges, lemons, and limes, provides a steady income for farmers who rely on the sale of these fruits in local and regional markets [90]. Additionally, it generates employment opportunities at various stages like planting, pruning, harvesting, and packaging during the cultivation process. The recent trends in production shows that orange from Nepal has potential for export if improved cultivation practices and the adherence to quality standards can be maintained [91]. Citrus orchards, with their scenic beauty and fragrant blossoms, can attract tourists, contributing to the growth of agro-tourism in the region.

4.1.3. Challenges

Despite the favorable geoclimatic conditions, the production and post-harvest storage of citrus crops in Nepal encounter significant challenges, posing a notable impact on overall productivity. One primary issue arises from insufficient grafting seasons and the provision of substandard saplings by local nursery vendors. This results in a mismatch between the demand for citrus crops and the available supply, adversely affecting productivity levels. Inadequate grafting seasons hinder the proper establishment of citrus orchards, impacting the growth and yield of these valuable crops. The use of substandard saplings further exacerbates the problem, as it compromises the overall health and resilience of the citrus plants, leading to reduced productivity and unmet market demands [92, 93]. Furthermore, post-harvest challenges pose a significant hurdle to the citrus industry in Nepal. Inadequate storage practices contribute to substantial fruit losses after harvest [94]. Without proper storage facilities and techniques, citrus fruits are susceptible to spoilage, deterioration, and decay, rendering a considerable portion of the harvest unsuitable for consumption or commercial purposes. This not only results in economic losses for citrus farmers but also affects the overall supply chain and market availability of citrus products [95, 96]. The National Research Citrus Program (NCRP), a government body of Nepal, is working towards to uplift the overall citrus farming. Standard grafting procedures are followed to produce disease free and quality saplings [97]. However, use of cutting-edge technologies, such as the IoT, remains essential. This not only facilitates remote monitoring and control of environmental parameters but also enables the recording of sensor data for insightful data analytics [98].

This study aims to provide a suitable implementation of IoT technology as one of the crucial transformative solutions for grafting and post-harvest storage of Mandarin Orange in Nepal. By leveraging IoT system, the aim is to address the shortcomings in grafting practices, optimize irrigation through microclimate regulation, and introduce real-time monitoring and control mechanisms for post-harvest storage conditions. The main contribution of this work is the demonstration that the integration of an IoT system in citrus farms and crops can improve the productivity, reduce waste, and contribute to the long-term food security of the region.

The two challenges considered to be of main interest were off-season grafting and post-harvest storage. For this purpose, IoT system is implemented, and the performance is evaluated.

4.2. Related Works

Over the years, there have been significant technological developments in areas such as managing nurseries, orchards, protecting plants, and handling post-harvest processes. Strano et al. discussed the challenges of post-harvest losses in citrus, primarily in the Mediterranean

Basin, where it is a significant fruit source. These losses, attributed to diseases and metabolic disorders, can reach up to 30 to 50% of the total production. To mitigate this, there is a critical need for innovative post-harvest technologies aimed at preserving quality and extending shelf life. The emphasis lies on the proper handling, treatment, storage, and transport of harvested produce. Strano et al. intended to provide a critical review of current knowledge regarding safe and sustainable strategies as well as advanced post-harvest handling and storage technologies [99]. Mario et al. presented the effectiveness of two treatments, namely hot water dipping (HWD) at 50 °C for 3 min and hot air treatment (HAT) at 37 °C for 48 h, in managing chilling injury and decay in blood oranges during cold quarantine and subsequent storage. The study proposed HWD as a commercially viable option for mitigating chilling injury and decay in quarantined fruit while advising caution against the use of HAT to enhance the keeping quality of blood oranges following cold disinfestation [100].

A study conducted in Khuzestan, Iran, aimed to reduce post-harvest losses in Valencia and local Siavarz orange cultivars. Treatments following optimal harvesting included hot water dipping, thiabendazole (TBZ) fungicide, wax, and combinations. After fruit storage at 6 ± 1 °C and 85–90% humidity for 3 months, the results showed hot water, wax, and TBZ effectively reduced post-harvest decay, particularly against penicillium molds. For Siavarz, these treatments notably reduced decay to 2% compared to the control's 26.7%. While wax preserved fruit weight, ascorbic acid, and firmness, hot water treatment maintained weight and firmness but lowered ascorbic acid content [101]. Raithore et al. explored a sensor-based electronic tongue system's (e-tongue) ability to differentiate between orange juices from healthy and Huanglongbing (HLB)-affected oranges. By analyzing key chemicals impacting flavor and health, the e-tongue detected variations in orange juice spiked with sucrose, citric acid, potassium chloride, and secondary metabolites [102].

Lafuente et al. suggested that blue light-emitting diode (LED) light, under the specified conditions, has positive effects on the post-harvest storage of Lane Late oranges, including enhancing resistance against pathogens and influencing beneficial metabolic activities. However, it is essential to note that the effectiveness of such treatments can depend on various factors, including the specific conditions, duration of exposure, and the type of fruit being studied [103]. Hu et al. studied the effect of light on ripe Hamlin sweet oranges after harvesting. They used light-emitting diodes (LEDs) and ultraviolet (UV) light for six days. By examining important ripening factors and analyzing the contents of sugars, acids, and color components in the orange pulps, it was found that LED and UV light not only made the oranges ripen faster but also changed their sugar, acid, and color content significantly [104].

Zhang et al. examined the impact of blue LED light intensity on carotenoid accumulation and gene expression related to carotenoid biosynthesis in satsuma mandarin and Valencia orange juice sacs in vitro. It was found that 100 μmol m−2 s−1 blue LED light was effective in increasing carotenoid content, particularly β-cryptoxanthin in satsuma mandarin, while 50 μmol m−2 s−1 blue LED light induced carotenoid accumulation, specifically all-trans-violaxanthin and 9-cis-violaxanthin, in Valencia orange. The value μmol m−2 s−1 expresses the light saturation point (LSP). The LSP is the point at which the photosynthesis rate does not increase any further despite increasing light intensity. When this point is reached, the photosynthesis-rate curve becomes flat.

Gene expression analysis revealed concurrent upregulation of key carotenoid biosynthesis genes, corresponding with increased carotenoid accumulation under specific blue LED light intensities. These findings contributed to understanding the regulatory mechanisms of carotenoid accumulation influenced by blue LED light [105]. Hussain et al. explored the specific ramifications of climate change on citrus cultivation, focusing on temperature variations, water availability, light intensity, atmospheric CO2 concentration, and salinity stress. Innovative strategies such as advanced monitoring systems, precision irrigation, molecular priming, and shade netting were discussed as potential solutions to mitigate the adverse effects of environmental stressors, fostering a more resilient citriculture capable of addressing the challenges posed by climate change [106]. Luca Preite et al. explored the significant challenges facing agriculture, notably the need to produce more food due to population growth, which increases pressure on natural resources like water and land. To investigate how innovative strategies can reduce water consumption in agriculture, the authors conducted a systematic review of studies from the last ten years, using PRISMA guidelines and the Scopus database [107,108]. The review focused on approaches like controlled-environment agriculture, hydroponics, and precision farming for field crops. The findings suggested these strategies could potentially reduce water consumption, but additional research is needed to evaluate their full impact and potential trade-offs. The results aimed to establish a framework for assessing sustainable agricultural practices and how these strategies can be applied in real-world scenarios [109].

Cao et al. revealed that the combined treatment of blue light and ethylene facilitated chlorophyll degradation, hastening fruit color change through gene expression modulation. These results contributed to understanding the regulatory mechanisms of blue LED light irradiation on enhancing the coloration of ethylene-degreened satsuma mandarin fruit [110]. J.H. Bower et al. investigated the impact of ethylene on Bartlett pear quality during storage at −1 or –2 °C. The study suggests that while minimizing ethylene is desirable, effective temperature management plays a more critical role in preserving fruit quality [111]. Sheik et al. in their review paper explored the distinction between traditional and smart agriculture. They also identified various sensors crucial for smart agriculture and their integration with emerging technologies, emphasizing the need to address research challenges for enhanced adoption and deployment in the future [112]. The significance of using the IoT to enhance productivity and cost effectiveness in agriculture was highlighted by Rehman A. et al. in their paper. The research focused on evaluating smart agriculture through IoT approaches, showcasing applications, benefits, current challenges, and potential solutions [113].

N.N Mishra et al. in their review explored the transformative impact of the IoT and big data on agri-food systems. The review discussed their roles in agriculture, and supply chain modernization as well as social media's influence on the food industry, food quality assessment, and safety measures [114]. M.N. Mowla et al. in their study advocated for sustainable agriculture through automation, focusing on integrating the IoT and wireless sensor networks (WSNs). The research emphasized the need for advanced technology adoption to ensure efficient annual production. It provided a comprehensive overview of IoT-WSNs and wireless network protocols, addressing recent challenges and proposing mitigation strategies for the future development of smart agriculture systems [115]. M. Ayaz et al. in their review identified current trends, future prospects, and potential research challenges in the integration of IoT with traditional farming practices [116]. Kour et al. in their study highlighted the transformative role of the IoT in enhancing both the quality and quantity of the agriculture sector. They emphasized globally collaborative efforts involving scientists, research institutions, and nations, aiming to harness IoT's potential for resource optimization [117].

R.K. Singh et al. in their study introduced Agri Fusion, a multidisciplinary architecture for efficient agriculture solutions, highlighting industrial solutions and proposing a step approach for performance evaluation in precision agriculture (PA). the study also outlined open research issues and future scopes in implementing precision agriculture [118]. S. Qazi et al. in their survey paper offered a comprehensive tutorial on advancements in smart agriculture through IoT and AI, critically reviewed challenges in their deployment, and discussed future trends, both technological and social, anticipating widespread adoption by farmers globally [119]. G. Burchi et al. in the paper [120] highlighted the importance of upgrading greenhouse cultivation technology in Mediterranean countries like Italy, Turkey, Greece, and Spain. These regions are crucial for fresh food production and ornamental plant export, yet they lack advanced techniques. The "HouseGarden High Tech" project addressed this gap by introducing a network of sensors and information and communication technology (ICT)-based automation. This high-tech greenhouse, with its sophisticated data-driven control system and non-thermal plasma (NTP) technology, aims to optimize crop management, improve yields, and streamline operations. The project underscored the need for modern technology to enhance productivity and sustainability in greenhouse cultivation.

Zhang, R. et al. used machine learning to provide a theoretical basis for determining the shelf life of blueberries under different storage temperatures, offering technical support for predicting their remaining shelf life [121]. Strano, M.C. et al. emphasized the significant post-harvest losses in Citrus spp., which can reach 30 to 50% of the total production due to diseases and metabolic disorders. To address these issues, the paper explored innovative post-harvest techniques and sustainable strategies aimed at reducing losses, improving quality, and extending shelf life. These approaches included improved handling, storage, and transport practices, along with a focus on reducing synthetic fungicide residues and their environmental impact [16].

4.3. Methodology

In this section, we delve into the details of the methods and materials employed in the grafting of citrus fruit within a polyhouse and the subsequent post-harvest storage of local mandarin oranges. The key aspects of monitoring and regulating temperature, relative humidity, and gas play a crucial role in both these processes. To ensure precision and efficiency in this regard, an IoT-based system was designed and implemented. The IoT system was developed, and the generated data were hosted in the cloud server. Users can login with verified credentials to access the system and use web or mobile application for real-time data visualization and monitoring. **Figure 4.1** depicts the IoT system architecture for polyhouse grafting and post-harvest cold storage applications. The subsequent sections provide a comprehensive breakdown of the specific methods and materials essential for the successful conduction of these experiments.

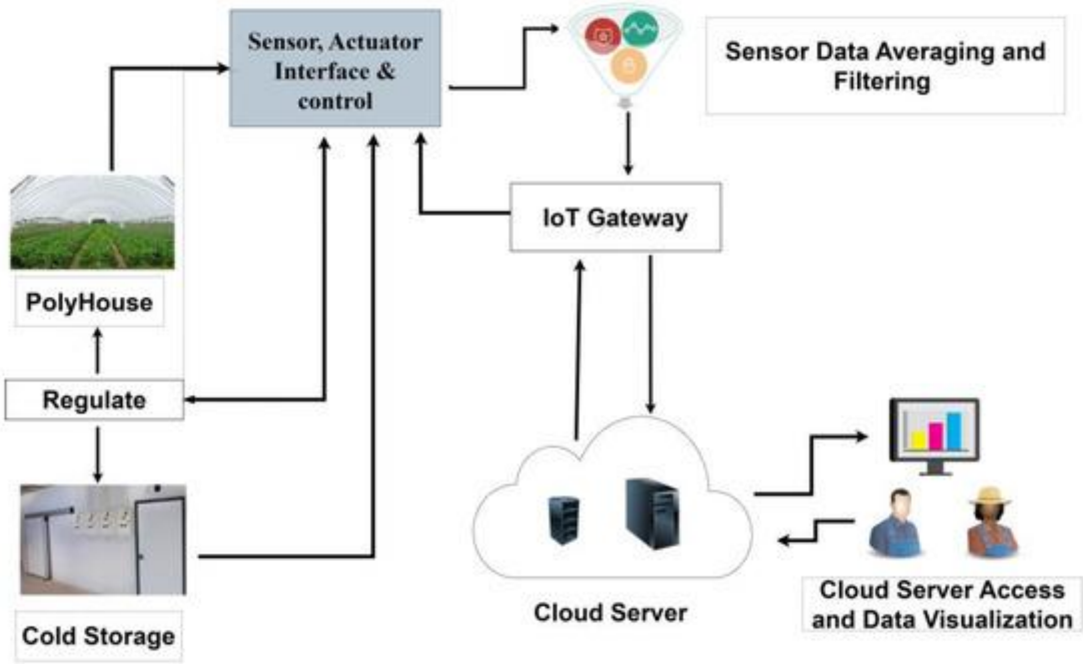

Figure 4.1 IoT system Architecture

4.3.1. Off-Season Grafting in Polyhouse

The study was conducted by designing a controlled environment inside a polyhouse facility equipped with sensors and IoT-controlled systems, which include an exhaust fan, fogger, heater, and cooling pads. The facility provided an ideal setting for grafting experiments, ensuring optimal conditions for citrus plants. Additionally, ambient temperature and relative humidity were continuously monitored using dedicated sensors strategically placed inside the polyhouse. A data-logger system facilitated real-time logging of climatic data, and a cloud server platform was employed for storing and retrieving the logged information. Quality scions and rootstocks of citrus plants suitable for grafting were also procured for the experimental setup. The methodology employed in this study involved the deployment of temperature and humidity sensors in the citrus orchard during the regular grafting season, which usually is November–January. These sensors continuously monitored and recorded ambient temperature and relative humidity, with data being sent to a cloud server for storage. To ensure accuracy, periodic checks were conducted to verify the sensors' functionality and the reliability of the recorded climatic conditions. Grafting activities took place during the regular season, usually in an open field within a low tunnel. The monitoring data showed that temperature fluctuated between 15 and

30 degrees Celsius, while humidity ranged from 80% to 95%. However, the ambient temperature and humidity was not ideal for open-field grafting after the month of February. To extend the grafting operation period, experiments were conducted inside the polyhouse with a controlled environment mimicking the optimal conditions observed during the regular season.

4.3.2. Post-Harvest Storage of Mandarin Orange

The materials utilized in this experimental study included local mandarin oranges harvested at the optimal ripening stage. The oranges were graded to ensure uniformity and quality. The experiment involved five different treatments labeled T_1–T_5. In treatment T_1, oranges were stored in open trays without any additional covering. Treatments T_2 through T_5 used clean low-density polyethylene (LDPE) plastic bags, with each treatment having a different number of holes in the bag to control the airflow around the oranges during storage. The objective was to determine the best storage method among those commonly used in the region. To this end, the study evaluated three distinct storage facilities, which are illustrated in **Figure 4.2**. This setup aimed to assess which storage approach provided the optimal conditions for preserving oranges.

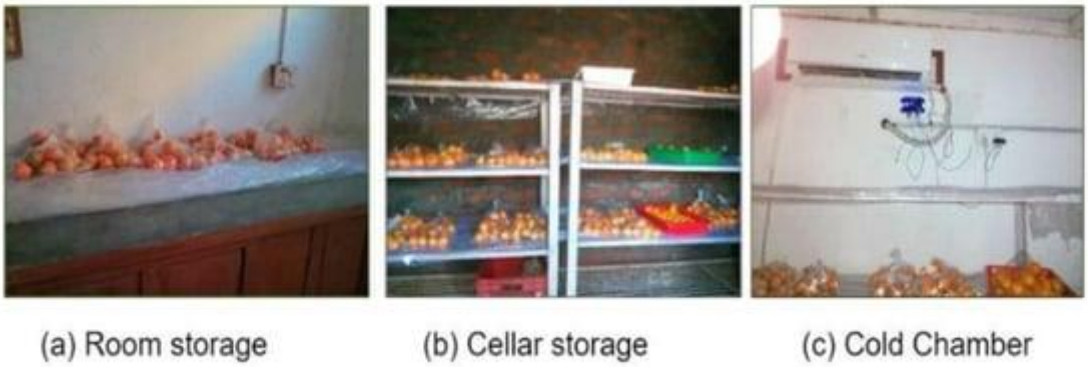

Figure 4.2 Mandarin orange storage facilities

The description for the three storage facilities is given below:

Table 4.1 outlines the key characteristics of each storage facility, including their dimensions, temperature range, relative humidity range, and a brief description.

Table 4.1 Description of storage facility

Storage Facility	Dimensions (m)	Temperature Range (°C)	Relative Humidity Range (%)	Description
(a) Room Storage	4 x 5 x 9	20-25	75-85	Standard room storage with ambient conditions.
(b) Cellar	3 x 4 x 7	15-19	75-85	A controlled cellar environment.
(c) Cold Chamber	3 x 4 x 7	10-12	75-85	Cold chamber for cooler storage.

The methodology employed in this experiment aimed to evaluate the post-harvest storage conditions of mandarin fruits, focusing on different treatments and storage setups. Initially, a meticulous fruit selection process was conducted, ensuring uniformity and the absence of damage in the chosen mandarin fruits. Subsequently, five distinct treatments (T_1–T_5) were established, incorporating varying storage conditions and utilizing trays and plastic bags with different numbers of holes to regulate airflow. The post-harvest storage experiment spanned a duration of 12 weeks, with each treatment being replicated three times to ensure result reliability. For T_1, mandarin fruits were placed directly on open trays, while T_2–T_5 involved bagging the fruits in clear plastic bags with two, four, six, or eight holes, respectively, for controlled airflow. The treatments were allocated to specific storage conditions, including room storage, cellar storage, and cooling storage. Throughout the experiment, environmental conditions within each storage facility, encompassing temperature and humidity, were regularly monitored and recorded. Destructive sampling was implemented, extracting three fruits as samples from each treatment per week to assess quality attributes such as firmness, color, and taste (data not included here). The collected data, including observations of decay or spoilage, were meticulously recorded, and a comprehensive statistical analysis was undertaken to discern the impact of different storage treatments on the post-harvest quality of mandarin fruits.

4.3.3. Proposed IOT System and Implementation

Figure 4.3 illustrates the architecture of the proposed IoT system. This system is specifically designed for two applications: polyhouse grafting and post-harvest storage of mandarin oranges. The proposed IoT system integrates various sensors, including the DHT22 for temperature and humidity, a light intensity sensor, and a CO_2 sensor, all interfaced with a NodeMcu-12E, an ESP8266-based controller. In the polyhouse grafting phase, sensors continuously monitored temperature, humidity, and light, essential for successful citrus grafting. The ESP8266-based microcontroller preprocessed the sensor data and transmitted to a cloud server at regular intervals. Actuators such as exhaust fan, humidifier, and fogger adjusted conditions based on sensor data to maintain optimal temperatures between 15 to 30 degrees Celsius and optimal humidity levels of 75 to 85%. Full-spectrum light-emitting diode (LED) lights ensured an adequate 12–16 h of light exposure in the polyhouse.

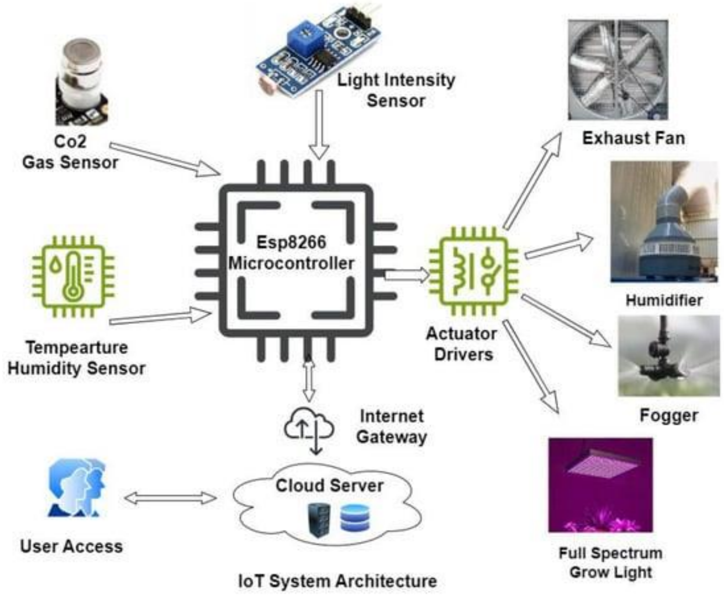

Figure 4.3 Proposed IoT system

For post-harvest storage, a cold chamber was equipped with real-time monitoring sensors for temperature, humidity, and CO_2 concentration. The system allowed remote monitoring, and actuators adjusted conditions to maintain recommended storage parameters for mandarin oranges. The temperature was kept between 7 to 10 degrees Celsius, and relative humidity was maintained between 75% to 90%. The stored data were not only accessible remotely but could also be visualized and downloaded for further analysis. This feature enables growers to make informed decisions and fine-tune environmental parameters. **Figure 4.4** shows the implementation of the IoT system for grafting inside a polyhouse and cold chamber storage for postharvest. The use of IoT technology in both grafting and post-harvest storage facilities enables remote monitoring and automatic control, thereby reducing manual intervention and ultimately contributing to improved citrus cultivation practices.

Figure 4.4 Implementation site. (a) Grafting activities and polyhouse of NCRP, Dhankuta, Nepal. (b) Cold storage located at Syangja, Nepal

4.4 Result and Discussions

4.4.1. Offseason Grafting in Polyhouse

Figure 4.5 depicts temperature and humidity variations in a polyhouse during the months March–April, without any internal regulation. Temperature and humidity readings showed clear fluctuations over time, indicating a range of environmental conditions. The temperature readings, taken over several days, varied significantly, with low readings in the range of 16 to 25 degrees Celsius during early morning and late-night hours. Temperatures tended to peak during the daytime, reaching 40 degrees Celsius or sometimes even higher to 50 degrees Celsius. Humidity readings displayed a contrasting pattern. Early-morning and late-night readings tended to show high humidity levels, often above 90%. However, as the temperature rose throughout the day, humidity generally decreased, sometimes falling below 20%. This cyclical pattern of temperature and humidity throughout the day suggests that environmental conditions are influenced by daily weather changes and sunlight. Understanding these variations is crucial for applications inside a polyhouse, as they directly impact plant growth, irrigation needs, and other critical processes.

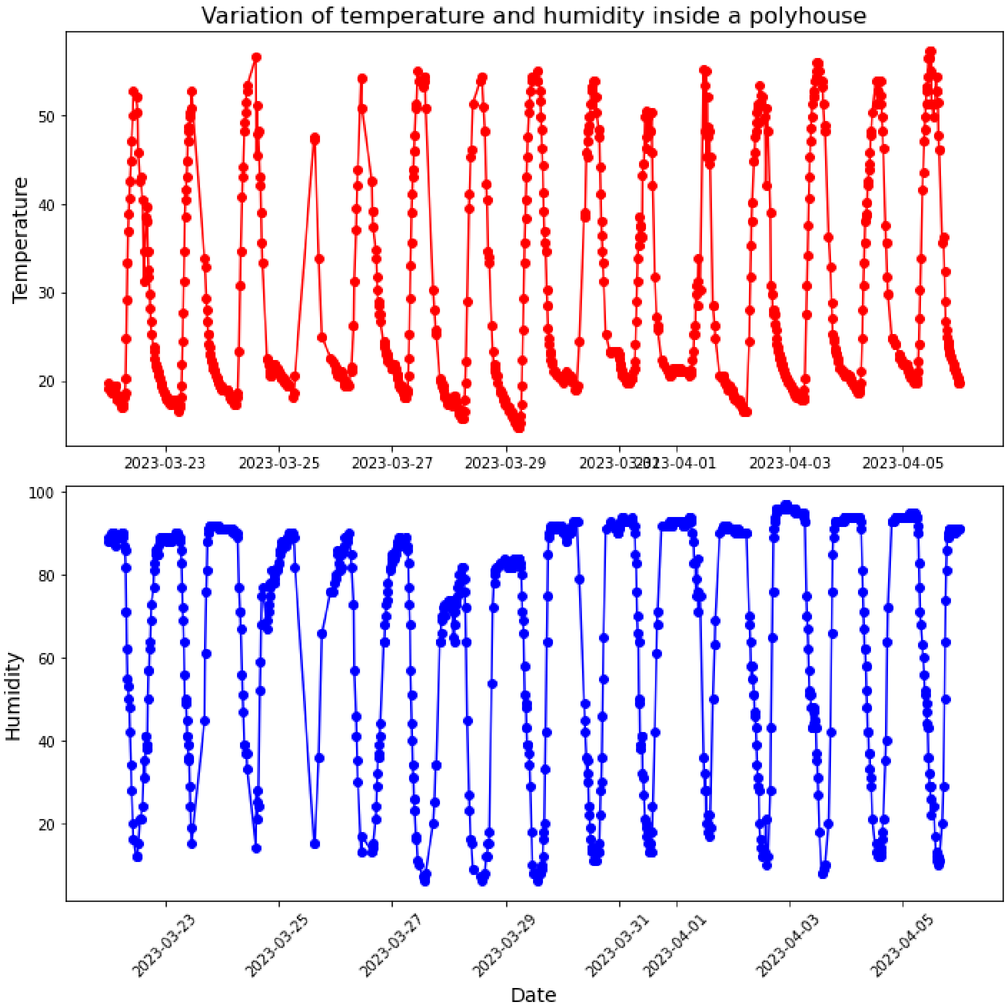

Figure 4.5 Variation of temperature and humidity inside a polyhouse

For the successful cultivation of graftage plants, it is imperative to maintain specific climatic conditions and selection of a proper scion, i.e., root stock. Ideally, the temperature should be regulated within the range of 15 to 35 degrees Celsius, and relative humidity levels should be maintained between 70% to 90%. These optimal conditions are crucial for the healthy development and grafting success of citrus plants. Therefore, the necessity of implementing an internal microclimate regulation system within the polyhouse is evident. To counter the substantial temperature and humidity fluctuations observed within the polyhouse, a control system was implemented using the proposed IoT system. Using exhaust fans, cooling pads, and foggers, this system acted swiftly to regulate the internal microclimate. Sensors continuously monitored temperature and humidity, activating the exhaust fan and fogger systems when deviations occurred, ensuring they remained within the optimal range of 15 to 35 degrees Celsius for temperature and 70% to 90% for humidity. Additionally, the integration of a cloud server enabled remote monitoring of sensor data, allowing real-time insights and facilitating prompt decision making for optimal polyhouse conditions.

An experiment was conducted to assess the success rates of different grafting types for acid lime (Sunkagati-2 scion on trifoliate rootstock) and mandarin orange (Avana Aprino scion on trifoliate rootstock). Three grafting types, namely veneer, splice, and cleft, were employed, and the results are summarized in the **Table 4.2** below:

Table 4.2 Summary of grafting and success rate

S.No	Crop	Scion	Rootstock	Grafting Type	Total Grafted Plant	Success	Success rate (%)
1	Acid Lime	Sunkagati-2	Trifoliate	Veneer	109	99	90.8
2	Mandarin Orange	Avana Aprino	Trifoliate	Veneer	36	33	91.7
3	Mandarin Orange	Avana Aprino	Trifoliate	Splice	36	26	72.2
4	Mandarin Orange	Avana Aprino	Trifoliate	Cleft	36	22	61.1

The veneer grafting type demonstrated remarkable success rates for both acid lime and mandarin orange, at 90.8% and 91.7%, respectively. The splice and cleft grafting types for mandarin orange, while yielding acceptable success rates of 72.2% and 61.1%, revealed a comparatively lower efficacy than the veneer method. These findings emphasize the importance of selecting an appropriate grafting method, with the veneer technique standing out as highly effective for both acid lime and mandarin orange. This result suggests that for off-season grafting for acid lime and mandarin, trifoliate orange rootstock and the veneer grafting method is recommended. This result also contributes valuable insights for citrus-grafting practices, enabling farmers and horticulturists to make informed decisions for optimal yield and success rates in citrus grafting.

4.4.2. Post-Harvest Storage of Mandarin Orange

The experiment conducted involving different storage facilities, such as a normal room, cellar, and cold chamber, and with varying treatments and replications revealed significant insights into the storage of oranges. **Figure 4.6** is shows the comparative results obtained. Among the storage options, the cold chamber emerged as the most suitable for preserving the quality and extending the shelf life of oranges compared to normal room and cellar storage. **Figure 4.7**, **Figure 4.8** and **Figure 4.9** depict the reduction in the weight and shrinkage of mandarin oranges, indicative of physiological weight loss (PWL) which is expressed as PWL (%) = (Initial Weight/(Initial Weight−Final Weight))×100. PWL was found to be at its minimum when stored in a cold chamber, followed by cellar storage and room storage over a 49-day period. **Figure 4.10** corresponds to decay loss in different storage facilities. The least loss, at 8%, occurred in cold chamber storage, while the highest, at 13%, was observed in normal room conditions. In a parallel storage experiment using LDPE poly bags (25 microns), the least effective method for preserving was found to be normal room storage with fruit on a plastic tray, yielding a shelf life of 32 days. In contrast, storing fruit inside an LDPE poly bag with eight holes and under the same storage conditions extended the shelf life to 62 days.

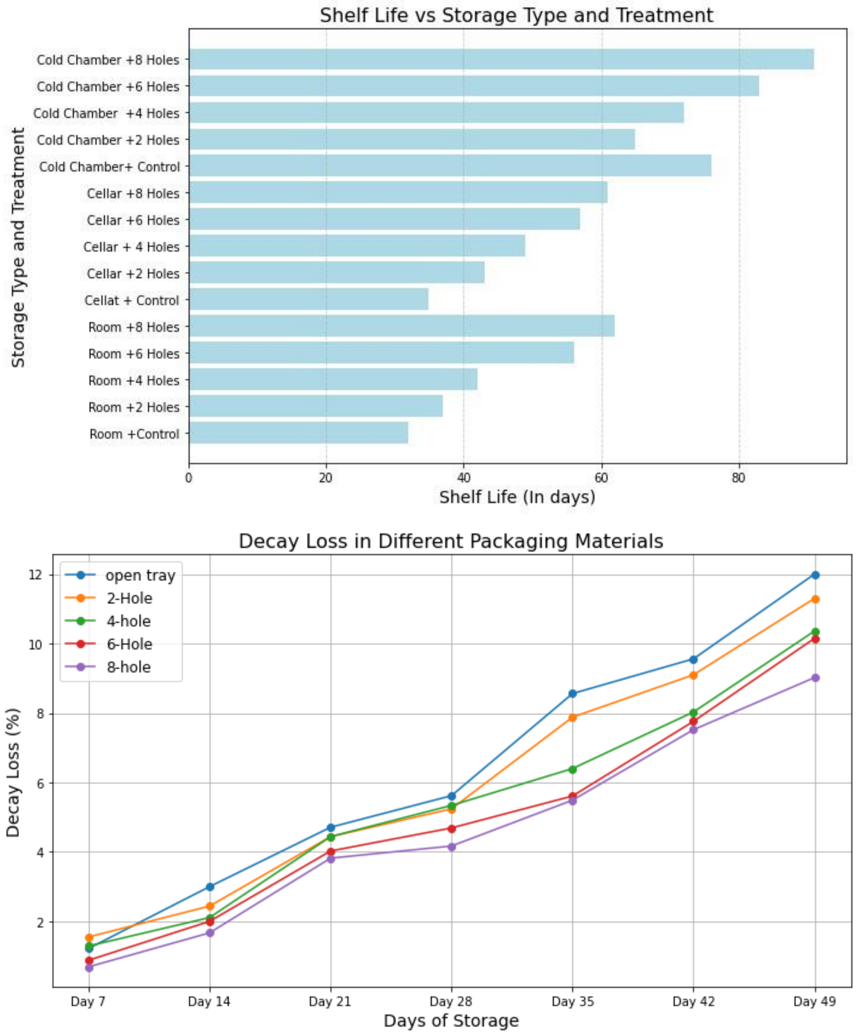

Figure 4.6 Combined treatment and shelf life in days and decay loss (%)

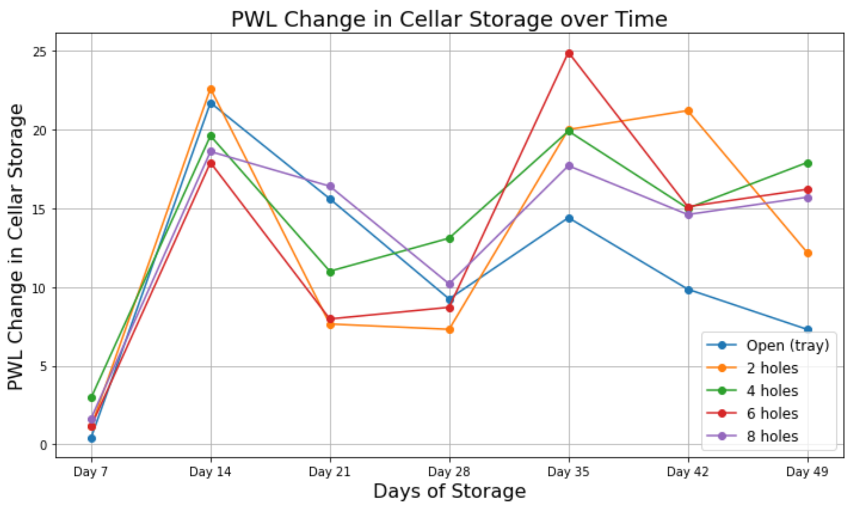

Figure 4.7 PWL change in cellar storage over time

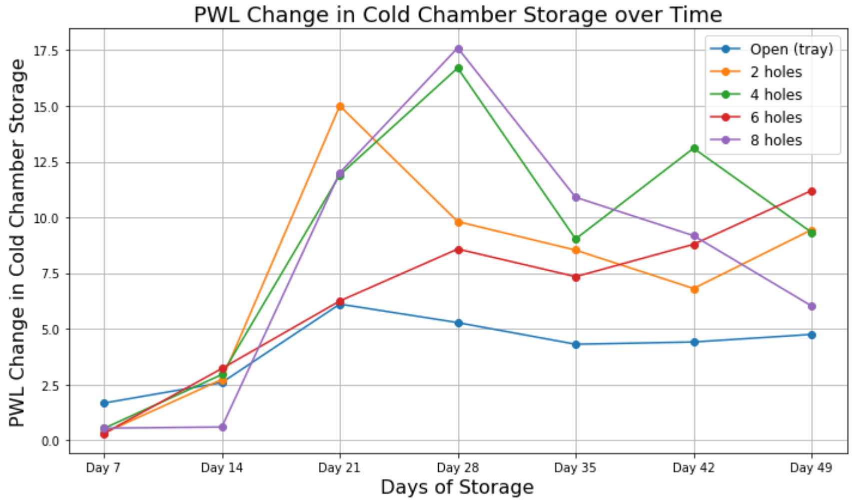

Figure 4.8 PWL change in cold chamber storage over time

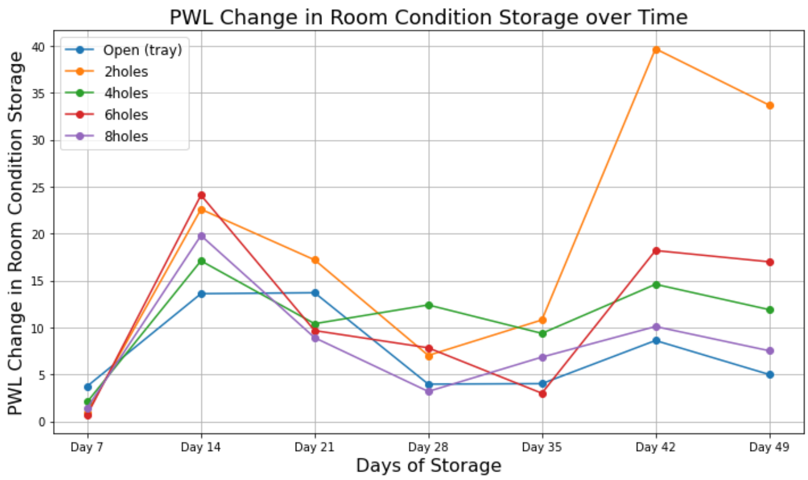

Figure 4.9 PWL change in room condition storage over time

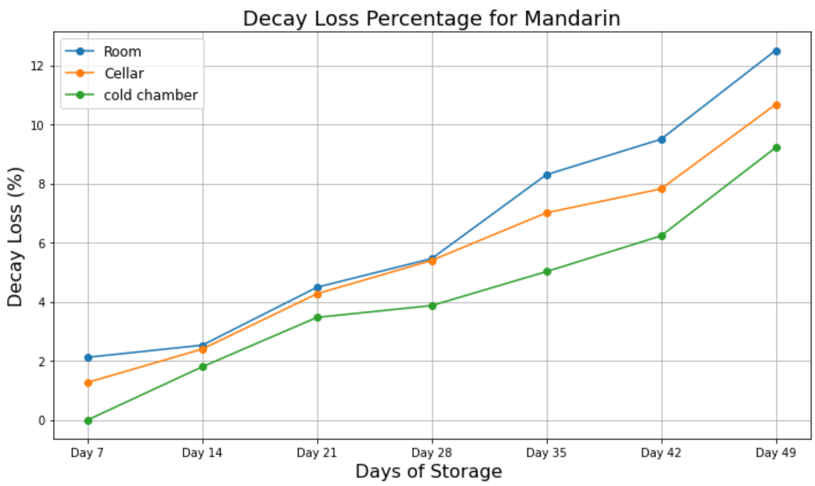

Figure 4.10 Decay loss percentage for mandarin

The cold chamber demonstrated the highest overall shelf life among the three storage structures, and when using LDPE poly bags with eight holes under the cold chamber, the shelf life was extended to three months. In summary, the cold chamber emerged as the most suitable storage option for maintaining orange quality and extending shelf life compared to room and cellar storage. Notably, the inclusion of eight holes in the plastic bags was crucial for enhancing airflow, contributing significantly to prolonged shelf life and reduced decay.

4.4.3 Total Soluble Solids (TSS) to Titratable Acidity (TA) ratio

TSS/TA ratio (total soluble solids to titratable acidity ratio): This ratio is a measure used in fruit quality assessment. Total soluble solids (TSS) typically represent sugars and other dissolved solids in the fruit juice, while titratable acidity (TA) measures the acidity level, usually as citric acid. The ratio provides insights into the balance between sweetness (TSS) and acidity (TA) in the fruit. **Table 4.3** presents detailed information on the TSS/TA ratio at various storage durations (15, 30, 45, and 60 days of storage (DOS)) across different conditions, namely normal room, cellar, and cold storage, as well as with different LPDE plastic packaging types (control, two holes, four holes, six holes, and eight holes). The results highlight that normal room storage and cellar storage generally maintain higher TSS/TA ratios, indicating better preservation of fruit sweetness compared to cold storage. Additionally, the table provides statistical metrics including SEM (standard error of the mean), F-values from ANOVA (analysis of variance), LSD (least significant difference) values, and significance levels determined by DMRT (Duncan's multiple range test). The SEM values (e.g., 0.22 and 0.32) reflect the precision of the TSS/TA ratio measurements at different DOS. F-values (***, **, *, and ns) indicate the significance of differences between treatment groups, with *** indicating highly significant differences. LSD values (e.g., 1.1) determine if mean differences are statistically significant at a significance level of 0.05 (5%), while "ns" denotes no significant difference between means at the specified level. DMRT aids in identifying specific treatments that significantly differ in TSS/TA ratios, contributing to a comprehensive understanding of citrus fruit quality and stability under varied experimental conditions.

Table 4.3 Effect of storage conditions and TSS/TA ratio of local mandarin orange

Treatments	TSS/TA ratio			
	15 DOS	30 DOS	45 DOS	60 DOS
Storage conditions (Factor A)				
Room	8.12a	9.97	11.4	15.24a
Cellar storage	8.68a	9.89	10.92	12.76b
Cold storage	6.79b	9.56	10.88	11.43c
Sem (±)	0.22	0.32	0.16	0.38
F-value	***	ns	ns	***
LSD0.05	0.65			1.1
Plastic packaging (Factor B)				
Control	8.76a	10.35	12.08a	15.95a
Two Holes plastic packaging	7.74b	8.92	11.05b	13.26b
Four Holes plastic packaging	7.59b	10.05	10.58b	12.16bc
Six Holes plastic packaging	7.61b	9.52	11.10b	13.27b
Eight Holes plastic packaging	7.63b	10.19	10.52b	11.08c
Sem (±)	0.29	0.42	0.21	0.49
F-value	*	ns	***	***
LSD0.05	0.87	-	0.61	1.42
CV, %	11	12.8	5.7	11.2
Grand Mean	7.87	9.81	11.07	13.15

SEM (±): The standard error of the mean (SEM) indicates the precision of the sample mean as an estimate of the population mean. It shows how much the sample mean is expected to vary from the true population mean. The values (e.g., 0.22 and 0.32) denote the SEM for each TSS/TA ratio measurement at different DOS.

F-value: The F-value is from the analysis of variance (ANOVA) and indicates whether the differences between treatment groups (e.g., storage conditions or packaging types) are statistically significant. Asterisks (***, **, *, and ns) indicate the significance level of the F-value, with *** meaning highly significant and ns meaning not significant.

LSD value (LSD0.05): LSD stands for least significant difference. It is a measure used in statistical hypothesis testing to determine if the difference between two means is statistically significant. The value (e.g., 1.1) represents the LSD at a significance level of 0.05 (5%), which is used to compare means and determine if they are significantly different.

ns: “ns” stands for “not significant”. In the context of the table, it means that there is no statistically significant difference between the means compared at the specified significance level (typically $p = 0.05$).

DMRT (Duncan's multiple range test) is a statistical test used after ANOVA and shows significant differences among treatments. It compares the means of all treatment pairs to see which ones differ significantly.

4.5 Real-time monitoring and control of commercial cold storage

Previously, farmers encountered challenges when mandarin oranges stored in large cold chambers began to deteriorate within just a month [**12**]. Manual operation of temperature and humidity controls in cold storage facilities, along with the absence of a real-time and automated system for gas exhaust, significantly contributed to the degradation of the oranges. Consequently, recommendations were made for enhancing both pre-harvesting and post-harvesting procedures, highlighting the critical need for integrating advanced automation systems to effectively regulate storage environments. These findings underscore the importance not only of selecting optimal storage facilities but also of implementing cutting-edge technologies to ensure the longevity and quality of stored produce. **Figure 4.11** showcases the 5 days of sensor data obtained at 10 min intervals from the deployed IoT device from 27 January 2024 to 31 January 2024, illustrating the real-time monitoring capabilities. The temperature and humidity sensor data were securely logged in to the cloud server for monitoring purposes every 10 min. Notably, the variation in temperature and humidity was consistently regulated within the desired range of 7 to 10 degrees Celsius with a relative humidity of 80–95%, ensuring optimal conditions for the preservation of mandarin oranges. Purposed IoT platform was deployed for real-time monitoring and visualization of sensor data. **Figure 4.12** illustrates the implemented version of application dashboard

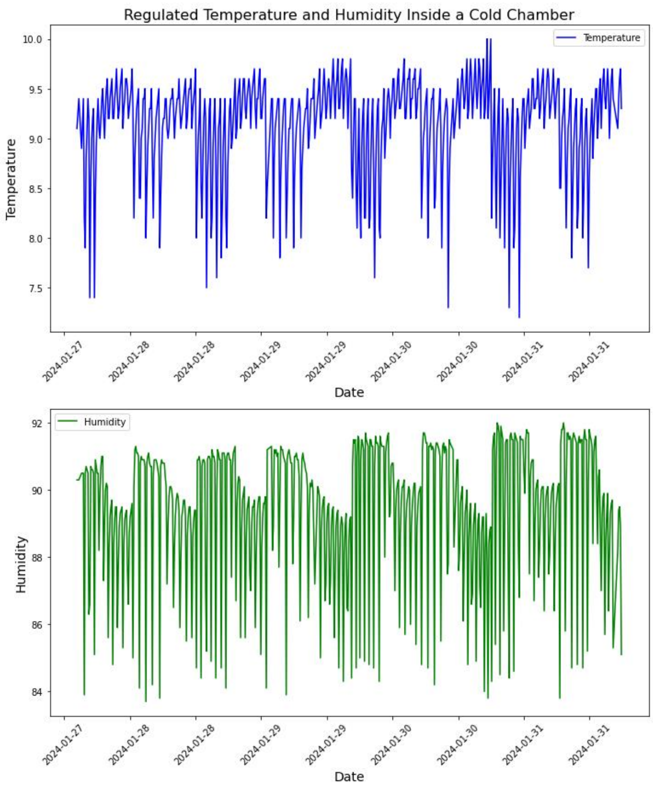

Figure 4.11 Regulated temperature and humidity inside a cold chamber

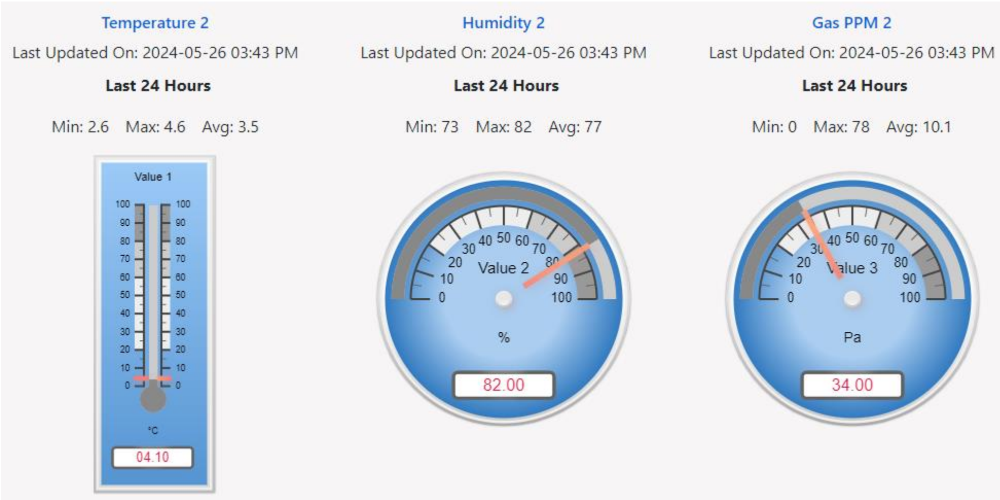

Figure 4.12 Application dashboard

4.6 Discussion

This research demonstrates the implementation of IoT technology in off-season grafting of citrus in polyhouses, an innovative and relatively new concept in agricultural practices in Nepal. The proposed system extends the traditional regular-season grafting period, enabling the production of quality saplings and meeting the demand for citrus fruits outside the regular season. By regulating and monitoring climatic conditions, the system facilitates successful grafting practices when natural conditions are less favorable. IoT devices monitor temperature, humidity, and other environmental factors to maintain optimal conditions in the polyhouse. This precision reduces risks such as poor graft union and low survival rates of grafted plants. This study highlights the importance of selecting appropriate grafting methods, scion, and rootstock to enhance success rates during off-season grafting. The veneer grafting type with trifoliate rootstock demonstrated remarkable success rates for both acid lime and mandarin orange at 90.8% and 91.7%, respectively. The other aspect of this research includes pre-harvest recommendations to the farmers to optimize the quality of mandarin oranges. This aspect is significant because many farmers may not be aware of these practices or may neglect them when preparing fruits for storage, which has previously led to decay and spoilage. First, a preliminary surface washing with clean water is recommended to remove contaminants. Following this, immersing the fruit in a 4% calcium chloride solution for 4 min helps improve the fruit’s texture and durability during storage. To ensure effective drying, treated fruits should either air dry overnight or be dried with warm air to avoid excess moisture during storage. Applying a protective layer of citrus wax is crucial in maintaining freshness and preventing moisture loss. After this, fruits should be swiftly stored in sanitized trays within 24 hrs of harvest to minimize contamination. Storage conditions are critical; maintaining a temperature between 7 and 10 degrees Celsius and relative humidity of 75–95% preserves fruit quality and reduces spoilage. In this study, we compared various post-harvest storage methods to identify best practices. We identified several key recommendations and best practices for post-harvest storage of fruit, focusing on the cold chamber environment. These practices aim to maintain fruit quality and extend shelf life, emphasizing the importance of hygiene, temperature control, and real-time monitoring. The results revealed that normal room storage and cellar storage maintained a higher total soluble solids to titratable acidity (TSS/TA) ratio, indicating they preserved fruit sweetness better than cold storage. In terms of plastic packaging, the control group (no holes) consistently yielded the highest TSS/TA ratio, suggesting that limiting airflow could help maintain fruit quality. At 60 days of storage (DOS), normal room storage and the control group performed best, indicating their effectiveness in preserving fruit quality over time. However, for longer-duration storage with less decay and spoilage, cold storage may be preferable due to its controlled environment, reducing the risk of mold and other decay-related losses. These results suggest that a combination of room storage for short-term quality retention and cold storage for long-term preservation may offer the best approach. Physiological weight loss (PWL) is at its minimum in cold storage. It was found that cold storage provided the highest shelf life compared to cellar and normal room storage. Cold storage is recommended for long-term storage due to its ability to minimize decay and spoilage through controlled conditions. In conclusion, the proposed system's integration of IoT technology in real-time monitoring of cold storage enables precise control and quick responses to deviations, which helps in taking immediate corrective action. This also ensures optimal storage conditions.

4.6.1 Limitation of the Study

This study has some limitations that should be acknowledged. First, the research was conducted within the specific climatic conditions of Nepal's hilly regions, which may limit the generalizability of the findings to other regions with different climates. Second, the study focused primarily on mandarin oranges and acid limes, and further research is needed to validate the applicability of the proposed methods to other citrus varieties and fruit types. Additionally, while the IoT technology demonstrated significant benefits, the initial cost of implementation and the need for technical expertise may pose challenges for small-scale farmers.

4.7. Conclusions

Citrus fruit cultivation, particularly mandarin oranges, holds significant economic importance in Nepal's hilly regions, benefiting from favorable geoclimatic conditions. However, challenges such as inadequate grafting techniques, poor sapling quality, and ineffective post-harvest storage practices hinder the sector's growth. This research explores these challenges and proposes innovative solutions through the integration of IoT technology. The research emphasizes two critical areas for improvement: enhancing off-season grafting techniques and optimizing post-harvest storage methods. Off-season grafting, facilitated by IoT-monitored polyhouse, demonstrated remarkable success rates for acid lime and local mandarin orange varieties. This approach not only extends the grafting season but also ensures higher-quality saplings, addressing a longstanding issue in the citrus-farming community. Farmers are encouraged to follow pre-harvest recommendations for preparing the fruits for post-harvest storage. Furthermore, the study meticulously evaluated various post-harvest storage methods—normal room storage, cellar storage, and cold chamber storage—for mandarin oranges. Farmers can plan how they store their fruit after harvesting, as the farmers may have varying production capacities. Farmers can strategically prioritize their post-harvest approach for short-term, medium-term, and long-term storage. The cold chamber emerged as the most effective method, maintaining optimal conditions that minimized physiological weight loss (PWL). Analyzing various storage methods, the study found that normal room storage and cellar storage maintained higher total soluble solids to titratable acidity (TSS/TA) ratios, indicating better fruit sweetness retention, while cold storage was more suitable for long-term storage with reduced decay. Crucially, IoT-enabled real-time monitoring within the cold chamber played a pivotal role in regulating temperature, humidity, and gas composition, thereby significantly reducing post-harvest losses and extending shelf life. These findings emphasize the transformative potential of IoT technology in revolutionizing mandarin orange cultivation practices in Nepal. By integrating IoT solutions in both grafting and post-harvest stages, farmers can enhance productivity, improve product quality, and ultimately uplift their livelihoods. Moreover, the study's recommendations for pre-harvest practices offer practical insights for farmers to optimize fruit quality and longevity. Looking ahead, continued research and adoption of IoT applications hold promise for further enhancing agricultural practices in Nepal's citrus sector. Future efforts should focus on expanding IoT's role in monitoring and optimizing other aspects of citrus farming, ensuring sustainable growth and resilience in this vital agricultural industry.

Chapter 5: Conclusion

This thesis has examined the transformative potential of Internet of Things (IoT) technology in agriculture, with a focus on smallholder farmers in Nepal. The research demonstrates how IoT can address key challenges in the agricultural sector to improve productivity and support broader sustainability objectives. The core of this research is involved in the design and implementation of a low-cost, reliable, and customizable IoT platform specifically for smallholder farmers in low- and middle-income countries like Nepal. This platform integrates sensors for real-time monitoring, allowing farmers to manage crop and livestock data through web and mobile applications.

The practical use of this platform in off-season citrus grafting and post-harvest storage demonstrates innovation in addressing challenging agricultural conditions. The thesis highlights the importance of making technology adaptable and accessible to small farmers in rural areas, addressing a critical need in agricultural development. The proposed IoT architecture integrates sensor networks, edge computing, and cloud computing to create a cost-effective and user-friendly IoT system. Field experiments were conducted to validate the platform's reliability, in differenet agricultural scenarios suitable for smallholder farmers and community farming. The platform's efficient data management over extended periods was demonstrated, handling significant volumes of sensor data. A real-world application of this platform in regulating the microclimate for off-season citrus grafting achieved results comparable to on-season grafting, validating the platform's effectiveness in improving agricultural efficiency and productivity.

Specific challenges in citrus cultivation in Nepal's hilly regions were addressed in this research, including inadequate grafting techniques, poor sapling quality, and ineffective post-harvest storage methods. IoT solutions were proposed to improve off-season grafting techniques and optimize post-harvest storage. The use of IoT-monitored polyhouses for grafting acid lime and mandarin oranges significantly improved grafting success rates and sapling quality. Evaluating various post-harvest storage methods, the research found that IoT-enabled cold chamber storage was the most effective in maintaining optimal conditions and reducing post-harvest losses. These findings underscore the potential of IoT to enhance citrus cultivation practices, improve fruit quality, and extend shelf life, ultimately benefiting farmers and improving their livelihoods.

Additionally, the thesis has highlighted the critical role of agriculture in Nepal's economy, contributing significantly to nation's GDP and providing employment for a large portion of the population. This study identified IoT as a key technology to bridge the gap between traditional and modern agricultural practices, empowering farmers, improving food security, and promoting sustainable farming. By enabling real-time monitoring and precision agriculture, IoT mitigates risks from climate variability, optimizes resource utilization, and enhances market access, ultimately improving the livelihoods of smallholder farmers.

The thesis provided an in-depth exploration of IoT fundamentals, including its applications, architecture, connectivity properties, and platforms. The core components of IoT systems—sensors, connectivity solutions, and data analytics platforms—were analyzed, illustrating how these elements integrate to enable efficient communication and data exchange, fostering operational efficiency and autonomous decision-making. The architecture of IoT systems, composed of perception, network, and application layers, ensures scalability and flexibility. Key platforms such as AWS IoT, Microsoft Azure IoT, and Google Cloud IoT were discussed in terms of their roles in device management, data collection, and integration. Connectivity options like Wi-Fi, Bluetooth, Zigbee, LoRaWAN, and cellular networks were evaluated for their suitability in various agricultural applications. This section also detailed essential IoT components in agriculture, including sensors, actuators, processors, and edge devices, and how they contribute to real-time monitoring, control, and optimization, ultimately supporting more efficient and sustainable farming operations. Global case studies further demonstrated IoT's potential to revolutionize traditional agricultural practices. These examples illustrated how IoT could address challenges and promote sustainable agricultural practices across diverse sectors.

In conclusion, this research provides a strong foundation for the development and implementation of IoT-based agricultural systems tailored to smallholder farmers in Nepal. The proposed IoT platform, focused on cost-effectiveness, reliability, and ease of use, has shown significant promise in real-world applications. Its integration in grafting and post-harvest processes offers potential to enhance agricultural productivity, improve product quality, and contribute to sustainable farming practices.

5.1 Future Work

This research provides a foundation for implementing IoT technology in agriculture for smallholder farmers in Nepal, yet several areas require further exploration.
We suggest conducting long-term studies to evaluate the sustained impact of IoT on farmers' livelihoods and assessing the scalability of IoT applications across various crops and conditions. Integrating advanced technologies like artificial intelligence, big data analytics, and blockchain with the IoT platform could enhance efficiency and data management.

Understanding the socio-economic implications of IoT adoption is crucial. Future research should identify cost-reduction strategies, such as subsidies and community models, to enhance accessibility for farmers. Additionally, developing training programs will empower farmers to effectively use IoT technologies.

Finally, examining the environmental impact of IoT and engaging farming communities in the research process will ensure relevant solutions. Addressing these areas will significantly enhance the potential of IoT in agriculture, benefiting smallholder farmers in Nepal and beyond.

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Appendix A

Curriculum Vitae

Ritu Raj Lamsal

Experience

Adjunct Professor (2023 – to date)
Little Angles College (Kathmandu University)
Kings College, (Westcliff University)

Asst. Research Director (2022–2023)
Deerwalk Institute of technology, Kathmandu, Nepal

HoD, Electronics Department
(2016–2022)
Deerwalk Institute of technology, Kathmandu, Nepal

Associate Professor, HoD EEE Department (2006-2010)
VSB Engineering College,

Satellite Broadcast Engineer (2001-2004)
Channel Nepal Television

Education

PhD Telecommunication Engineering (Thesis submitted) (2018–2024)
University of Malaga, Málaga, Spain

M.Tech VLSI Design (2004–2006)
Bharath University, India

BE Electronics and Communication Engineering (1995–1999)
Institutions of Engineers, India

Publications

- R.R. Lamsal, P Karthikeyan, P. Otero y A. Ariza. "Design and implementation of IoTplatform targeted for smallholder farmers: from Nepal perspective". *Agriculture* (MDPI. ISSN: 2077-0472), 2023, 13, 1900. DOI: 10.3390/agriculture13101900.

- Lamsal, R.R.; Acharya, U.K.; Karthikeyan, P.; Otero, P.; Ariza, A. Implementing Internet of Things for Real-Time Monitoring and Regulation of Off-Season Grafting and Post-Harvest Storage in Citrus Cultivation: A Case Study from the Hilly Regions of Nepal. *AgriEngineering* **2024**, *6*, 2082-2100. https://doi.org/10.3390/agriengineering6030122

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- Lamsal, R.R., Devkota, A. & Bhusal, M.S. Navigating Global Challenges: The Crucial Role of Semiconductors in Advancing Globalization. *J. Inst. Eng. India Ser. B* **104**, 1389–1399 (2023). https://doi.org/10.1007/s40031-023-00938-4

Professional memberships

- Fellow Member of Institutions of Engineers India, FIE
- Registered Engineer, Nepal Engineering Council
- Member, Nepal Engineering Association