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IoT-ENABLED SMART DURIAN HARVESTING: AN INTEGRATED PLATFORM FOR REAL-TIME ORCHARD MONITORING AND SUSTAINABLE HARVEST MANAGEMENT

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ABSTRACT

Durian harvesting requires timely monitoring to ensure that fallen fruits are collected promptly, thereby reducing quality deterioration and potential economic losses. Traditional orchard monitoring relies heavily on manual inspection, making the process time-consuming, labour-intensive, and inefficient, particularly in large orchards. The Internet of Things (IoT) technology has been widely used in smart agriculture to manage orchards, but there are very few existing systems that combine real-time durian fall detection with a mobile application that sends immediate notifications, automatic image capture of fall events, and orchard management functions. This study develops an Integrated IoT-Based Smart Orchard Platform for real-time durian harvest management. The proposed platform combines an ESP32-CAM, an SW-420 vibration sensor, Firebase Realtime Database, and an Android mobile application. An adapted Design Science Research (DSR) methodology was employed, comprising problem identification, requirement analysis, system design, system development, and system evaluation. The System Usability Scale (SUS) was employed to assess the usability of the system, consisting of eight respondents. The evaluation yielded an average SUS score of 86.88, corresponding to an Excellent level of usability and high user satisfaction. The proposed platform provides a practical IoT-enabled solution for real-time durian harvest management and extends the application of digital agriculture more than environmental monitoring in harvesting activities. This study contributes to digital innovation by supporting data-driven orchard management and advancing sustainable agribusiness practices.

Keywords: *Durian Harvest Management, Internet of Things (IoT), Smart Orchard, Sustainable Agribusiness*.

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1. Introduction

The agricultural industry is a significant part of the Malaysian economy, especially in high-value fruit production. Durian is a tropical fruit with significant economic value due to its high demand in domestic and export markets (Fazlil Ilahi *et al*., 2024). Malaysia has become a major exporter of durians, as the plantation land has been expanding to satisfy the growing demand in the world. The expansion of durian plantations has led to management difficulties and complex operations, particularly in large-scale orchards (Fazlil Ilahi *et al*., 2024). Digital technologies such as the Internet of Things (IoT), cloud computing, artificial intelligence (AI), wireless sensor networks, and mobile technologies need to be embedded to assist farmers' activities in order to solve the farmers' problems.

These technologies help farmers to monitor field conditions continuously, collect data in real time, automate routine processes, and make decisions, ultimately improving productivity, resource efficiency, and sustainability (Dhal *et al*., 2024; Duguma & Bai, 2025). Among these technologies, IoT plays a central role by connecting sensing devices, cloud services, and end users into an integrated ecosystem that supports timely agricultural decision-making. Despite its growing adoption, challenges related to interoperability, communication reliability, scalability, and practical implementation continue to influence the successful deployment of IoT solutions in agriculture (Dhal *et al*., 2024).

In Malaysia, digital transformation has become an important strategy for strengthening the agricultural sector, particularly for high-value crops such as Durian. Premium varieties of durian, such as Musang King and Black Thorn, with high demand from local people and also for the export market, have further increased the commercial importance of durian cultivation, creating a greater need for efficient orchard management. Manual orchard monitoring is inefficient in terms of productivity and operational efficiency, especially when the farm size is large. Detecting fallen fruits is one of the most critical problems in durian farming. Durians fall naturally from the tree when ripe, unlike other fruits, and must be collected immediately to maintain quality and market value. This process is labour-intensive, time-consuming, and becomes increasingly inefficient as orchard size increases because fruit may fall at any time during the day or night. Delayed collection can compromise fruit quality, increase post-harvest losses, and negatively affect farm profitability (Wolfert *et al*., 2017; Duguma & Bai, 2025).

New technologies with the integration of digital technologies such as the Internet of Things (IoT), sensors, cloud computing, and mobile applications into agricultural operations has demonstrated considerable potential for improving farm operations through real-time sensing, wireless communication, cloud-based information management, and mobile applications. By automatically collecting and synchronising field information, these technologies enable farmers to access operational data remotely and respond more quickly.

However, current IoT applications remain largely concentrated on environmental monitoring, irrigation management, greenhouse automation, crop disease detection, and yield prediction. Comparatively less attention has been given to technologies that support real-time harvest management, particularly in tropical fruit orchards (Dhal *et al*., 2024; Elijah *et al*., 2018).

Thus, this study develops an Integrated IoT-Based Smart Orchard Platform for real-time durian harvest management. The proposed platform combines an ESP32-CAM, an SW-420 vibration sensor, Firebase Realtime Database, and an Android mobile application to automate harvest-event detection, capture harvesting information, synchronise data through cloud services, and provide farmers with real-time notifications. In addition to monitoring harvesting activities, the platform supports orchard registration, harvest history management, collection-status monitoring, and analytical dashboards that facilitate more informed operational decision-making.

This study aims to develop an Integrated IoT-Based Smart Orchard Platform for real-time durian harvest management. There are three main contributions. Specifically, the objectives are to develop an IoT-based mechanism for detecting durian fall events and sending real-time notifications, to integrate harvest monitoring with digital orchard management functions, and to evaluate the developed platform through functional testing and usability assessment using the System Usability Scale (SUS). This study also contributes to sustainable agribusiness in three main ways.

First, it introduces an integrated IoT-enabled platform tailored to the operational requirements of durian harvesting. Second, it demonstrates how embedded sensing devices, cloud computing, and mobile technologies can be combined into a unified digital ecosystem for real-time orchard management. Finally, the proposed platform is evaluated through functional testing and the System Usability Scale (SUS) to assess both its technical performance and practical usability.

2. Literature Review

2.1 Digital Agriculture and Smart Orchard Systems

To improve agricultural productivity and sustainability, the emergence of Agriculture 4.0, with the integration of digital technologies such as the Internet of Things (IoT), cloud computing, artificial intelligence (AI), wireless sensor networks, and mobile applications, should be emphasized in Malaysia. These technologies enable farmers in agribusiness to continuously monitor farm environments, collect real-time data, automate analysis, and make evidence-based decisions to improve resource utilisation and operational efficiency. With that, it is important to adopt digital agriculture as a strategy to meet increasing food demand, to reduce the problem of labour shortages, and to address climate-related challenges while increasing sustainability in farming practices (Dhal *et al*., 2024; Wolfert *et al*., 2017).

IoT has become one of the key enablers of smart agriculture because it facilitates communication between sensing devices, cloud platforms, and end users (Dhal *et al*., 2024; Elijah *et al*., 2018). Agricultural systems embedded with IoT usually consist of sensors, embedded controllers, wireless communication networks, cloud databases, and mobile applications (Dhal *et al*., 2024; Tzounis *et al*., 2017). The integration of cloud computing further enhances these systems by enabling remote access, real-time data synchronisation, and historical data storage, allowing farmers to monitor agricultural activities regardless of location (Dhal *et al*., 2024; Tzounis *et al*., 2017). Consequently, IoT technologies have been widely adopted for applications such as precision irrigation, environmental monitoring, livestock management, crop health assessment, and farm automation (Dhal *et al*., 2024; Elijah *et al*., 2018).

The adoption of IoT has also expanded into smart orchard management, where digital platforms are increasingly used to monitor environmental conditions and improve orchard productivity (Tzounis *et al*., 2017; Wolfert *et al*., 2017). Existing smart orchard systems commonly employ sensors to measure temperature, humidity, soil moisture, rainfall, and light intensity, enabling more efficient irrigation scheduling and crop management (Tzounis *et al*., 2017; Dhal *et al*., 2024). These systems demonstrate the ability of digital technologies to enhance farm operations through continuous monitoring, automated information management, and improved decision-making (Wolfert *et al*., 2017; Dhal *et al*., 2024). However, most existing solutions primarily focus on environmental sensing rather than operational activities such as harvesting, leaving opportunities for further innovation in real-time orchard management (Dhal *et al*., 2024).

Digital technologies in agriculture aim to generate business value by improving labour productivity, reducing operational costs, supporting evidence-based decision-making, and enhancing long-term farm competitiveness (Wolfert *et al*., 2017; Dhal *et al*., 2024). For high-value fruit industries such as durian production, digital technologies have the potential to

improve operational efficiency while strengthening sustainable agribusiness practices (Dhal *et al*., 2024). Nevertheless, the adoption of integrated digital platforms remains limited among many orchard operators, particularly for technologies that support real-time harvesting operations (Dhal *et al*., 2024; Tzounis *et al*., 2017).

Past researchers stated that digital agriculture provides a strong technological foundation for modern farm management through IoT-enabled monitoring, cloud computing, and data-driven information systems (Wolfert *et al*., 2017; Dhal *et al*., 2024; Elijah *et al*., 2018). However, limited attention has been given to developing integrated smart orchard platforms that support real-time harvest management, particularly for tropical fruit crops (Dhal *et al*., 2024). This limitation provides the motivation for developing digital solutions that combine IoT sensing, cloud computing, and mobile applications to improve harvesting efficiency and operational decision-making (Dhal *et al*., 2024; Tzounis *et al*., 2017).

2.2 IoT-Based Real-Time Harvest Monitoring and Decision Support

For best productivity and sustainability in agribusiness, harvest management should be integrated with digital agriculture. Quality deterioration, post-harvest losses, pest infestation, and reduced market value are associated with the delay in harvesting. The intervention can be done through the implementation of the Internet of Things (IoT), focusing on the integration of sensors, embedded systems, wireless communication, cloud computing, and mobile applications, an IoT platform that provides farmers with real-time access to field information, allowing faster responses to operational events while reducing dependence on manual monitoring. (Dhal *et al*., 2024; Wolfert *et al*., 2017).

A layered architecture of Modern IoT-based agricultural systems consists of sensing devices, communication networks, cloud platforms, and user applications (Tzounis *et al*., 2017; Dhal *et al*., 2024). Embedded sensors collect field data, which are transmitted through wireless communication to cloud databases for storage and processing (Elijah *et al*., 2018; Dhal *et al*., 2024). In monitoring agricultural activities remotely, mobile or web-based applications are used to present the processed information to end users in the form of notifications, dashboards, and historical records, enabling farmers to monitor agricultural activities remotely (Wolfert *et al*., 2017; Tzounis *et al*., 2017). This integrated architecture enables remote monitoring, real-time data synchronisation, and evidence-based decision-making while improving operational efficiency and reducing labour requirements (Wolfert *et al*., 2017; Dhal *et al*., 2024).

Beyond monitoring, IoT technologies have also facilitated the development of Decision Support Systems (DSS) that assist farmers in planning agricultural activities based on real-time information (Wolfert *et al*., 2017; Dhal *et al*., 2024). By integrating sensor data with cloud-based analytics, these systems support decisions related to irrigation scheduling, crop health monitoring, fertiliser management, disease detection, and yield prediction (Elijah *et al*., 2018). The combination of IoT sensing and decision support enables agricultural operations to become more proactive rather than reactive, thereby improving productivity and resource utilisation (Wolfert *et al*., 2017; Dhal *et al*., 2024). However, most existing decision support applications remain primarily focused on crop production, environmental monitoring, and precision farming, with comparatively limited attention given to operational harvest management and post-harvest decision support (Dhal *et al*., 2024).

IoT technology has also been applied directly to fruit harvesting. Putra *et al*. (2022) developed an IoT-based fruit harvester that integrates sensors, mobile technology, and cloud data logging to support harvesting activities and record fruit information in real time. More recently, Mahathir and Mat Nawi (2025) developed an IoT-based monitoring system for durian trees and fruit-fall events using sensors and camera-based monitoring. These studies demonstrate the potential of IoT technologies to support fruit harvesting activities beyond conventional environmental monitoring. Research on smart orchard management has similarly concentrated on environmental monitoring, fruit growth assessment, disease detection, and yield estimation using IoT technologies, computer vision, unmanned aerial vehicles (UAVs),

and artificial intelligence (Tzounis *et al*., 2017; Dhal *et al*., 2024). Although these technologies have significantly advanced precision agriculture, comparatively fewer studies have investigated real-time harvest monitoring, particularly within tropical fruit orchards (Dhal *et al*., 2024; Wolfert *et al*., 2017). Most reported systems continue to emphasise environmental monitoring and crop management, whereas integrated platforms that combine automated harvest detection, cloud-based information management, mobile notifications, and digital orchard management remain relatively uncommon in the current literature (Dhal *et al*., 2024; Wolfert *et al*., 2017).

Durian harvesting differs from that of many commercial fruit crops because premium fruits in Malaysia are traditionally collected only after naturally falling from the tree. As a result, the timely detection and collection of fallen fruits are essential for preserving fruit quality and maintaining market value (Siriphanich, 2011; Youryon & Supapvanich, 2022). Because fallen fruits are highly susceptible to contamination, physical damage, and rapid quality deterioration, they should be collected immediately after detachment to minimise post-harvest losses (Mohd Ali *et al*., 2021; Siriphanich, 2011). However, despite advances in digital agriculture, comparatively limited research has developed integrated IoT-enabled platforms specifically designed to support real-time durian harvest management by combining automated harvest detection, cloud-based information management, and mobile decision support. This limitation highlights the need for an integrated Smart Orchard Platform capable of improving harvesting efficiency while supporting sustainable agribusiness (Dhal *et al*., 2024; Wolfert *et al*., 2017).

2.3 Research Gap

The past literature shows that the adoption of the Internet of Things (IoT), cloud computing, artificial intelligence (AI), and wireless communication technologies has been considered in the agriculture industry. With these technologies, farmers or people in the agriculture industries be able to work on environmental monitoring, precision farming, automated irrigation, crop health assessment, and data-driven decision-making, which contributes to improving agricultural productivity and resource efficiency (Wolfert *et al*., 2017; Dhal *et al*., 2024). Even though sensing devices, cloud platforms, and mobile applications are integrated into IoT-based smart orchard systems to support remote monitoring and farm management (Tzounis *et al*., 2017; Elijah *et al*., 2018), several important research gaps remain.

First, according to prior researchers (Dhal *et al*., 2024; Wolfert *et al*., 2017), existing IoT-based agricultural systems primarily focus on environmental monitoring rather than operational harvest management. Most of the past studies have highlighted monitoring environmental parameters such as temperature, humidity, soil moisture, rainfall, and light intensity to improve crop production (Tzounis *et al*., 2017). Little attention has been given to digital agriculture related to the harvesting process, particularly the real-time detection and collection of harvested fruits (Dhal *et al*., 2024). As a result, harvesting remains largely dependent on manual observation despite being one of the most labour-intensive and time-critical agricultural activities (Dhal *et al*., 2024; Wolfert *et al*., 2017).

Next, the literature shows that existing smart orchard applications usually function as monitoring systems instead of comprehensive management platforms (Wolfert *et al*., 2017; Dhal *et al*., 2024). Only a few studies describe integrated platforms that combine automated operational functions with cloud-based information management and decision support (Tzounis *et al*., 2017; Dhal *et al*., 2024). This limitation minimises the ability of existing systems to support end-to-end orchard operations, highlighting the need for more integrated digital platforms that combine monitoring, information management, and operational decision support for daily orchard management (Wolfert *et al*., 2017; Dhal *et al*., 2024).

Third, research on IoT applications has given more attention to general crops or temperate fruit orchards. For example, Mahathir and Mat Nawi (2025) developed an IoT-based monitoring system for durian trees in Malaysia that uses sensors and camera-based monitoring

to detect fruit-fall events and provide real-time information. This study demonstrates the potential of IoT technology for monitoring tropical fruit harvesting. However, there is still a need for a more integrated platform that combines real-time harvest detection with cloud-based information management, mobile notifications, orchard management, harvest records, and decision support. In contrast, fewer studies address the unique operational characteristics of tropical fruit orchards, particularly durian cultivation (Tzounis *et al*., 2017; Dhal *et al*., 2024). Unlike many commercial fruits that are harvested directly from the tree, durian fruits in Malaysia are traditionally harvested only after naturally falling from the tree. This harvesting practice makes timely detection and collection essential for maintaining fruit quality and market value (Siriphanich, 2011; Youryon & Supapvanich, 2022). Because fallen fruits are highly susceptible to physical damage, contamination, and rapid quality deterioration, they should be collected immediately after detachment to minimise post-harvest losses (Mohd Ali *et al*., 2021; Siriphanich, 2011). However, relatively few published studies have reported IoT-enabled systems specifically designed to support real-time durian harvest management by integrating automated harvest detection with cloud-based information management and mobile decision support (Dhal *et al*., 2024; Wolfert *et al*., 2017).

Finally, although digital agriculture is increasingly recognised as a driver of agricultural sustainability, previous studies have largely evaluated technological performance rather than broader operational and business outcomes (Wolfert *et al*., 2017; Dhal *et al*., 2024). Little attention has been given to how IoT-enabled harvest management contributes to operational efficiency, labour optimisation, reduction of post-harvest losses, and sustainable agribusiness (Dhal *et al*., 2024). Therefore, the relationship between business performance and digital innovation within orchard management is not sufficiently explored (Wolfert *et al*., 2017; Dhal *et al*., 2024).

To overcome these limitations, this study proposes an Integrated IoT-Based Smart Orchard Platform that combines an ESP32-CAM, an SW-420 vibration sensor, Firebase Realtime Database, and an Android mobile application into a unified digital ecosystem for real-time durian harvest management. This study proposes better systems compared to many existing systems that primarily emphasise environmental monitoring, the proposed platform integrates automated harvest detection, cloud-based information management, mobile notifications, digital orchard management, and decision support within a single application. By embedding IoT components, the platform enables monitoring and operational management; this study extends the application of digital agriculture beyond environmental sensing and demonstrates a practical approach for supporting more efficient harvesting operations and sustainable agribusiness.

Table 1 summarises the key research gaps identified in the existing literature and highlights the contributions of the proposed study. It demonstrates that, although previous research has established the value of IoT in environmental monitoring and precision agriculture, limited attention has been given to integrated harvest management, particularly in tropical durian orchards. Accordingly, this study addresses these gaps by developing a unified platform that combines real-time harvest detection, cloud-based data management, mobile notifications, orchard management, and decision support. The proposed platform therefore extends the role of IoT in agriculture from environmental monitoring to operational harvesting and contributes to improved efficiency, reduced post-harvest losses, and more sustainable agribusiness practices.

Table 1. Summary of Research Gaps and Contributions

Research Area	Existing Research	Identified Gap	Contribution of This Study	Key References
Digital Agriculture	IoT supports precision farming and environmental monitoring	Limited emphasis on harvest management	IoT-enabled real-time harvest monitoring	Dhal *et al*. (2024); Wolfert *et al*. (2017)
Smart Orchard Systems	Environmental sensing and remote monitoring	Lack of integrated operational management	Integrated smart orchard management platform	Tzounis *et al*. (2017); Elijah *et al*. (2018)
Tropical Fruit Orchards	Studies mainly focus on temperate crops	Limited research on durian harvesting	Real-time durian harvest management	Siriphanich (2011); Youryon & Supapvanich (2022)
Agribusiness	Technology-focused evaluation	Limited assessment of operational and business value	Supports operational efficiency and sustainable agribusiness	Wolfert *et al*. (2017)

3. Research Methodology

3.1 Research Design

Design Science Research (DSR) methodology was adopted in this study to design, develop, and evaluate an IoT-enabled Smart Orchard Platform for real-time durian harvest management. This methodology is widely implemented in information systems research because it focuses on the development and evaluation of innovative technological artefacts that address real-world problems while contributing to both practical applications and scientific knowledge (Hevner *et al*., 2004; Peffers *et al*., 2007). DSR methodology is well aligned with this study, which developed the Smart Orchard Platform that integrates IoT sensing, cloud computing, and mobile technologies to reduce dependence on manual orchard inspection and improve access to real-time harvesting information

The study comprised five phases as shown in Figure 1: problem identification, requirement analysis, system design, system development, and system evaluation, following the Design Science Research process model proposed by Peffers *et al*. (2007). During the problem identification phase, the operational challenges associated with conventional durian harvesting were examined, particularly manual orchard patrols, delayed fruit collection, labour dependency, and limited access to real-time orchard information.

In this research, requirement analysis was conducted to determine the platform's functional and non-functional requirements. The features of the main functional requirements include automatic durian-fall detection, image capture, cloud-based data synchronisation, real-time notification, orchard and tree management, harvest history, collection-status monitoring, and analytical reporting. Meanwhile, usability, reliability, accessibility, responsiveness, and secure user authentication elements were under non-functional requirements.

Based on these requirements, the platform architecture and application modules were designed, implemented, and integrated into a unified IoT ecosystem. After that, functional testing and a usability assessment were conducted to determine whether the completed system satisfied the specified functional requirements and could be effectively used by potential users.

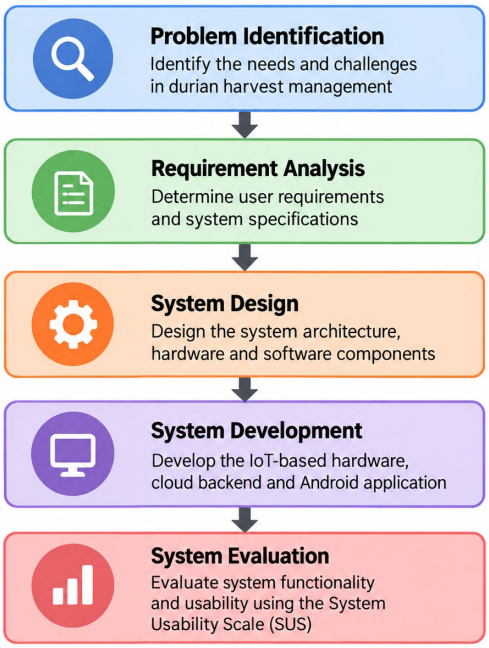


Figure 1. Research Process (adapted from Peffers *et al*., 2007)

The architecture provides real-time visibility of harvesting events and supports digital orchard management through integrated information services. However, the present study evaluates the platform in terms of functional performance and usability only. Therefore, potential benefits such as reduced labour requirements, lower post-harvest losses, or improved profitability should be regarded as expected operational benefits rather than confirmed outcomes, as these aspects were not directly measured in the system evaluation.

3.2 Proposed Smart Orchard System Architecture

The proposed Smart Orchard Platform employs a layered Internet of Things (IoT) architecture that integrates sensing devices, wireless communication, cloud services, and an Android mobile application. Such layered architectures are widely adopted in IoT-based agricultural systems because they facilitate data acquisition, communication, cloud processing, and user interaction through a unified digital ecosystem (Tzounis *et al*., 2017; Elijah *et al*., 2018; Dhal *et al*., 2024). In the proposed platform, harvesting events are detected in the orchard, transmitted via the Internet, stored in the cloud, and presented to farmers through a mobile interface.

At the sensing layer, an ESP32-CAM is integrated with an SW-420 vibration sensor. The vibration sensor detects disturbances generated when a durian falls onto the collection area. Once the measured vibration exceeds the predefined threshold, the ESP32-CAM automatically captures an image and generates a harvesting record containing the event timestamp together with the associated tree or orchard information.

The event data are transmitted through a Wi-Fi connection to the Firebase Realtime Database, which functions as the central repository for orchard profiles, tree records, captured images, harvest events, and collection status. Firebase Authentication is employed to manage secure user access, while real-time synchronisation enables newly detected harvesting events to be immediately reflected within the Android application. The use of cloud-based databases for real-time agricultural information management is consistent with current IoT-enabled smart farming architectures (Elijah *et al*., 2018; Dhal *et al*., 2024).

The Android application provides the primary user interface for monitoring and managing orchard activities. Its core functions include real-time harvest notifications, image viewing, orchard and tree registration, harvest history management, collection-status updates,

analytical dashboards, and map navigation. By integrating these functions into a single mobile application, the proposed platform supports both immediate harvesting responses and longer-term digital record management. The resulting operational workflow is illustrated below.

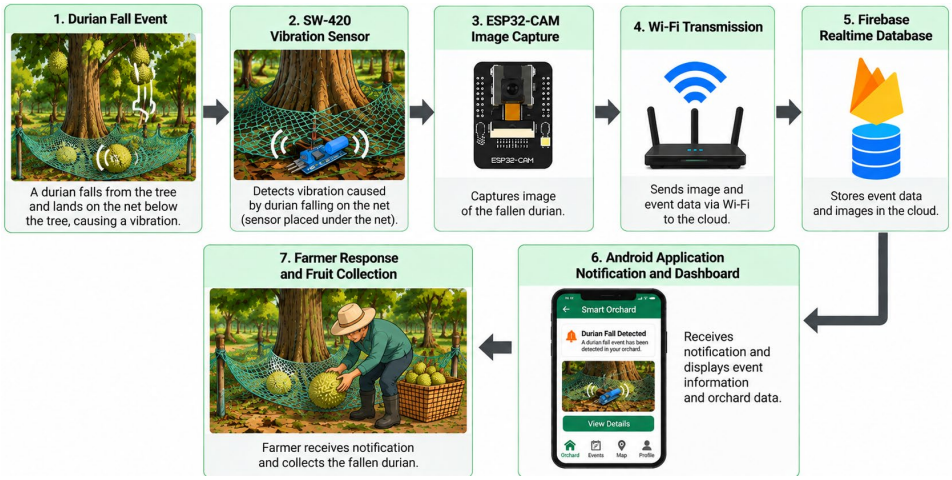


Figure 2. Information Flow of the Proposed Smart Orchard Platform

The proposed architecture as illustrated in Figure 2 transforms a conventionally manual harvesting process into an event-driven digital workflow by integrating IoT sensing, cloud computing, and mobile technologies. The architecture provides real-time visibility of harvesting events and supports digital orchard management through integrated information services. However, the present study evaluates the platform in terms of functional performance and usability only. Therefore, potential benefits such as reduced labour requirements, lower post-harvest losses, or improved profitability should be regarded as expected operational benefits rather than confirmed outcomes, as these aspects were not directly measured in the system evaluation.

3.3 System Evaluation

The platform was evaluated using two complementary methods: functional testing and usability evaluation. Functional testing examined whether the hardware, cloud services, and Android mobile application operated as an integrated system. The tested workflow included vibration detection, automatic image capture, Wi-Fi transmission, cloud storage, notification delivery, orchard-information management, harvesting-history retrieval, collection-status updates, and dashboard access. Each function was verified against the predefined functional requirements to ensure that the proposed platform operated as intended.

The usability evaluation involved eight participants aged between 23 and 58 years, all of whom had backgrounds related to durian orchard ownership or associated activities. The participants included durian farmers and orchard owners, individuals whose families owned durian orchards, a durian seller involved in managing a family orchard, and individuals who owned inherited or family-operated orchards. Their familiarity with durian-related activities provided relevant perspectives for evaluating the usability of the proposed Smart Orchard Platform. Following their interaction with the developed prototype, participants completed the System Usability Scale (SUS) questionnaire to assess the usability of the mobile application.

Usability was assessed using the System Usability Scale (SUS), a widely adopted and validated instrument for measuring the perceived usability of interactive systems (Brooke, 1996). Eight participants performed representative tasks using the Android application, including reviewing harvest notifications, monitoring orchard information, viewing harvesting records, and navigating the available modules. They subsequently completed the standard ten-item SUS questionnaire using a five-point Likert scale.

As tabulated in Table 2, the SUS score was calculated for each participant and converted to a score ranging from 0 to 100 in accordance with the standard SUS scoring procedure (Brooke, 1996). A benchmark score of 68 was adopted to represent acceptable usability, while higher scores indicate better perceived usability (Bangor *et al*., 2009). In addition, open-ended feedback was collected to identify issues related to interface clarity, ease of navigation, notification usefulness, and potential system improvements.

Table 2. Summary of evaluation methods

Evaluation method	Purpose	Main criteria
Functional testing	Verify system integration	Correct execution of required functions
Detection and image testing	Validate harvest-event capture	Successful vibration detection and image capture
Cloud synchronisation	Validate data communication	Successful storage and retrieval through Firebase
Notification testing	Verify real-time alert delivery	Notification received after a simulated event
SUS evaluation	Assess perceived usability	Ease of use, learnability, consistency, and confidence
User feedback	Identify improvements	Comments on interface and operational experience

4. Results and Discussion

4.1 Functional Evaluation of the Proposed Smart Orchard Platform

The functional evaluation verified that the proposed Smart Orchard Platform operated as an integrated IoT system capable of supporting real-time durian harvest management. The evaluation focused on validating the interaction between the hardware components, cloud infrastructure, and Android mobile application to ensure that harvesting events were detected, processed, synchronised, and presented correctly throughout the operational workflow. The evaluation confirmed that all core system functions operated according to the predefined functional requirements, demonstrating the successful integration of the proposed platform.

The evaluation showed that the ESP32-CAM and SW-420 vibration sensor successfully detected simulated durian fall events and automatically initiated the process. Once a harvesting event was detected, the captured image together with the corresponding harvesting information was transmitted through the Wi-Fi network to the Firebase Realtime Database. The harvesting record was subsequently synchronised with the Android application, enabling users to receive real-time notifications and immediately access the captured information. This event-driven workflow confirms that the proposed platform successfully supports automated harvest monitoring without requiring continuous manual observation.

The cloud infrastructure also demonstrated successful synchronisation across all application modules. Harvesting records, orchard information, tree profiles, collection status, and captured images were stored and retrieved correctly through Firebase without communication failures during functional testing. Users were able to register orchards, manage tree information, review harvesting history, update collection status, and monitor harvesting activities through the analytical dashboard. These findings indicate that the proposed architecture provides reliable integration between IoT sensing devices, cloud services, and mobile technologies, enabling digital management of orchard operations. This integrated architecture is consistent with IoT-based smart farming frameworks that combine sensing, cloud computing, and information management to support real-time agricultural operations (Elijah *et al*., 2018; Dhal *et al*., 2024).

In addition to harvest detection, the developed platform provides several integrated management functions that extend beyond conventional monitoring systems. The combination

of real-time notifications, digital harvest records, collection-status monitoring, and analytical dashboards enables farmers to access operational information through a single application. Rather than functioning solely as a harvest detection device, the proposed Smart Orchard Platform serves as a digital orchard management platform that supports information management and operational monitoring in a unified environment. This integrated approach is aligned with the principles of smart farming, where IoT technologies are used to support data-driven farm management and operational decision-making (Wolfert *et al*., 2017; Dhal *et al*., 2024).

Overall, the functional evaluation demonstrates that the proposed Smart Orchard Platform successfully achieved its intended objectives by integrating IoT sensing, cloud computing, and mobile technologies into a single operational platform. The successful execution of all functional modules indicates that the platform is technically reliable for supporting real-time durian harvest monitoring and provides a practical digital solution for orchard management. However, it should be noted that the functional evaluation verified system integration and operational performance only. Business outcomes such as labour savings, productivity improvement, and reduction of post-harvest losses were not directly measured in this study and therefore require further investigation in future research. Table 3 shows the summary of functional evaluation results.

Table 3. Summary of Functional Evaluation Results

Functional Module	Function	Evaluation Result
User Authentication	Secure user login and registration	Successful
Harvest Detection	Detect fallen durian using the SW-420 vibration sensor	Successful
Image Capture	Capture images automatically after harvest detection	Successful
Cloud Synchronisation	Synchronise harvesting data with Firebase	Successful
Real-Time Notification	Deliver harvest notifications to users	Successful
Orchard Management	Manage orchard and tree information	Successful
Harvest History	Store and retrieve harvesting records	Successful
Collection Status	Update harvested fruit collection records	Successful
Analytics Dashboard	Display harvesting information and summary statistics	Successful

4.2 Usability Evaluation

The usability of the proposed Smart Orchard Platform was evaluated using the System Usability Scale (SUS) to determine the level of user acceptance and the practicality of the Android mobile application for supporting real-time durian harvest management. Following functional testing, eight participants interacted with the application by performing representative tasks, including receiving harvest notifications, monitoring orchard information, reviewing harvest records, and navigating the application modules. They subsequently completed the standard ten-item SUS questionnaire using a five-point Likert scale. The SUS was selected because it is a widely recognised and reliable instrument for evaluating the usability of interactive systems (Brooke, 1996), with a score of 68 commonly adopted as the benchmark for acceptable usability (Bangor *et al*., 2009).

The evaluation produced an average SUS score of 86.88 as stated in Table 4, with individual participant scores ranging from 75.0 to 100.0. According to the SUS interpretation, this score falls within the Excellent (Grade A) category, indicating a high level of usability and user acceptance (Bangor *et al*., 2009). The results suggest that participants found the application easy to learn, straightforward to use, and suitable for supporting real-time monitoring of durian harvesting activities.

Qualitative feedback obtained during the evaluation further supported the quantitative findings. Participants indicated that the application was easy to understand and that the real-time notification feature effectively informed them of durian fall events. They also appreciated the clear presentation of harvesting information and considered the application helpful for

monitoring orchard activities. These observations indicate that the developed platform provides a positive user experience while meeting the usability requirements for practical deployment in orchard environments.

Overall, the usability evaluation complements the functional evaluation by demonstrating that the proposed Smart Orchard Platform is not only technically operational but also highly acceptable from the users' perspective. The combination of successful system integration and excellent usability provides evidence that the platform is suitable for supporting digital orchard management. Nevertheless, the usability assessment was conducted with a relatively small group of participants; therefore, broader evaluations involving a larger and more diverse population would further strengthen the generalisability of these findings.

Table 4. Summary of System Usability Scale (SUS) Results

Evaluation Metric	Result
Number of Participants	8
SUS Benchmark Score	68
Lowest SUS Score	75.0
Highest SUS Score	100.0
Average SUS Score	**86.88**
SUS Interpretation	**Excellent (Grade A)**

4.3 Discussion

The findings of this study demonstrate that the proposed Smart Orchard Platform successfully integrates IoT sensing, cloud computing, and mobile technologies into a unified platform for real-time durian harvest management. The functional evaluation confirmed that all core system modules operated according to the predefined requirements, while the usability evaluation indicated a high level of user acceptance, achieving an average System Usability Scale (SUS) score of 86.88. Collectively, these findings indicate that the proposed platform is both technically reliable and practical for supporting digital orchard management.

From a technical perspective, this study extends existing IoT-based agricultural applications by integrating multiple technologies into a single operational platform. Unlike many smart agriculture systems that primarily focus on environmental monitoring or individual sensing functions, the proposed platform combines automated harvest detection, image capture, cloud-based data synchronisation, real-time mobile notifications, digital record management, and analytical dashboards within one ecosystem. This integrated architecture is consistent with the direction of smart agriculture towards interconnected IoT ecosystems that combine sensing, cloud computing, and decision support for improved farm management (Wolfert *et al*., 2017; Dhal *et al*., 2024).

From an operational perspective, the proposed platform has the potential to support durian harvest management by providing automated harvest-event notifications and centralised access to orchard information. These features are expected to reduce dependence on routine manual inspections, support timely fruit collection, and improve the organisation of harvesting activities. However, the system was evaluated as a prototype and has not yet been deployed in an actual commercial durian orchard. Therefore, its operational benefits remain prospective rather than empirically demonstrated. Further field evaluation is required to determine its effectiveness in reducing manual inspections, improving collection response time, and minimizing post-harvest losses under actual orchard conditions. These findings are aligned with previous studies highlighting the potential of IoT-enabled technologies to support agricultural information management and operational decision-making (Elijah *et al*., 2018; Dhal *et al*., 2024).

From an agribusiness perspective, the proposed platform illustrates how digital innovation can support the digital transformation of orchard management. The integration of IoT sensing, cloud services, and mobile applications enables the digitalisation of harvesting

records and operational information, providing farmers with improved visibility of orchard activities. Rather than functioning solely as a harvest detection system, the platform serves as a digital management tool that supports information accessibility and operational decision-making. This observation is consistent with the broader objectives of digital agriculture, which seek to enhance farm productivity, information management, and long-term competitiveness through technology adoption (Wolfert *et al*., 2017). These capabilities are particularly relevant for high-value fruit industries such as durian production, where timely harvesting and effective information management are important for maintaining operational efficiency.

Overall, this study contributes to the growing body of digital agriculture research by demonstrating the feasibility of an integrated IoT-based solution for real-time durian harvest management. While many existing smart agriculture applications concentrate on crop monitoring and environmental sensing, the proposed platform addresses the comparatively underexplored area of harvest management for tropical fruit orchards. The successful implementation and positive usability evaluation support the growing body of evidence that integrated IoT technologies can facilitate digital transformation within agriculture while creating opportunities for more sustainable and data-driven agribusiness practices (Dhal *et al*., 2024; Wolfert *et al*., 2017).

Table 5 summarises the main contributions of the proposed Smart Orchard Platform. It shows how the platform combines IoT sensors, cloud computing, Firebase, and an Android application to support harvest detection, real-time notifications, digital records, and orchard management. The table also highlights the study's contribution to digital agriculture by focusing on real-time harvest management in tropical durian orchards. Although further field testing is needed, the platform shows potential to improve orchard operations and support digital transformation.

Table 5. Research Contributions of the Proposed Smart Orchard Platform

Contribution Area	Contribution of This Study
Technical Contribution	Integrates IoT sensing, cloud computing, Firebase, and an Android application into a unified harvest management platform.
Operational Contribution	Supports automated harvest detection, real-time notifications, digital harvest records, and orchard management.
Agribusiness Contribution	Demonstrates how digital technologies can support digital transformation and information management in durian orchard operations.
Research Contribution	Extends smart agriculture research by focusing on real-time harvest management for tropical fruit orchards.

5. Conclusion

This study proposed an Integrated IoT-Based Smart Orchard Platform to support real-time durian harvest management by integrating an ESP32-CAM, an SW-420 vibration sensor, Firebase Realtime Database, and an Android mobile application into a unified digital ecosystem. The proposed platform was developed to address the limitations of conventional durian harvesting, which relies heavily on manual orchard inspections and delayed fruit collection. By enabling automated harvest-event detection, cloud-based data synchronisation, and real-time mobile notifications, the platform provides farmers with timely access to harvesting information and supports more systematic orchard management.

The functional evaluation demonstrated that the proposed platform successfully integrated the hardware, cloud infrastructure, and mobile application to perform the intended operational functions. In addition, the usability evaluation produced an average System Usability Scale (SUS) score of 86.88, indicating a high level of user acceptance and confirming

that the platform is practical and easy to use. These findings demonstrate the feasibility of applying IoT technologies to support real-time harvest management for tropical fruit orchards.

This study contributes to digital agriculture by extending the application of IoT technologies beyond environmental monitoring to operational harvest management. The integration of automated harvest detection, cloud-based information management, and mobile decision support provides a practical approach for digital orchard management while contributing to the broader digital transformation of sustainable agribusiness. The proposed platform also establishes a foundation for future smart orchard applications that combine sensing technologies with operational information management.

Although the results are encouraging, this study has several limitations. The platform was evaluated using a prototype implementation and a relatively small group of participants, with the evaluation focusing primarily on functional performance and usability. Future research should involve larger-scale field deployments across multiple commercial orchards to evaluate system performance under different environmental and operational conditions. Additional enhancements may include the integration of artificial intelligence for automated fruit recognition, predictive harvest analytics, weather-based decision support, and drone-assisted orchard monitoring to further strengthen intelligent orchard management.

Practical challenges associated with actual orchard deployment should also be considered. Further investigation is needed to minimize false-positive detections caused by environmental disturbances such as strong wind, falling branches, heavy rainfall, and animal activity. In addition, power consumption and battery life should be evaluated to support continuous operation, particularly in remote orchard areas. Internet connectivity should also be examined, with alternative wireless communication technologies considered for orchards with limited network coverage. Addressing these aspects would help improve the robustness and suitability of the platform for long-term orchard deployment.

In conclusion, the proposed Smart Orchard Platform demonstrates the potential of integrating IoT sensing, cloud computing, and mobile technologies to support real-time durian harvest management. The study provides practical evidence that digital innovation can facilitate more effective orchard management and supports the continued adoption of smart technologies within sustainable agribusiness.

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Author Contribution

Norisan Abd Karim and Nur Carmilla Binti Abdullah Muhammad Shafiq contributed to the literature review, system design and development, data collection, system evaluation, and preparation of the manuscript. Nur'aina Daud contributed to the research content, interpretation of the findings, and review of the manuscript. Syibrah Naim and Syaheerah Lebai Lutfi reviewed the research content and the final manuscript before submission.

Declaration of generative AI in the writing process

During the preparation of this work, the authors used ChatGPT (OpenAI) for language and grammar assistance. The authors reviewed and edited all suggested content and take full responsibility for the content of the publication.

Data Availability/Supplementary Materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request

Ethics Statement

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health, and Environmental (HSE) protocols of Universiti Teknologi MARA.

Conflict of Interest

All authors state that they have no conflict of interest.

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