

CHAPTER I

INTRODUCTION

1.1. Research Background

Hydroponics is a modern agricultural method that has become increasingly popular as a practical response to the shrinking availability of conventional agricultural land (Marisa et al., 2021). This method is widely recognized for its ability to significantly improve water use efficiency. This system utilizes nutrient-enriched water as the primary growing medium, allowing plant growth conditions to be controlled more measurably compared to conventional methods. In the context of global challenges such as population growth, climate change, and agricultural land degradation, hydroponics serves as a relevant alternative solution to support food security. Specifically, it provides a practical cultivation method for communities facing limited agricultural land (Permata Sari et al., 2024). Along with technological advancements, various innovations have been implemented to increase the efficiency of hydroponic system management, notably through the utilization of the Internet of Things (IoT) in monitoring and automation systems. However, without a monitoring system capable of detecting condition changes rapidly and objectively, hydroponic management remains highly dependent on manual observation, which potentially leads to delays in decision-making.

As a practical implementation of a hydroponic system utilizing monitoring technology, this research was conducted at the Smart Green Garden located at the Undiksha Jinengdalem Campus, Buleleng Regency, Bali. The hydroponic system

employs the Deep Flow Technique (DFT), where the nutrient solution flows and is retained at a certain depth, keeping the plant roots partially submerged. This approach is commonly used in the cultivation of pakcoy (*Brassica rapa L.*). All cultivation pipes are interconnected within a single nutrient solution flow system, meaning that the water quality and nutrient distribution in each pipe heavily depend on the overall system's performance. Given this interconnected system configuration, monitoring water quality and ensuring the even distribution of nutrients become crucial aspects in maintaining the uniformity of growing conditions across all hydroponic pipes. Furthermore, maintaining optimal nutrient concentrations and a stable rootzone environment is essential for achieving high growth and yield in hydroponically cultivated pakcoy (Maludin et al., 2020).

Based on field observations, several problems were identified in the agricultural setup, such as algae growth and sediment accumulation in the water reservoir and hydroponic pipes. This causes an increase in water turbidity, a condition that has been shown to cause the yellowing of plant leaves (Aziezah et al., 2023). Subsequently, this deterioration in water quality can stunt plant growth and severely disrupt nutrient absorption by the roots. The variations in water levels were found across the hydroponic pipes, caused not only by differences in pipe inclination but also by the increased water demand of the plants during the late vegetative stage when they have reached maturity. This condition complicates manual monitoring processes when water shortages occur in certain sections of the pipes. Localized drought within a hydroponic system can induce water stress and wilting, as well as

decrease photosynthetic capacity, ultimately impacting the growth and quality of the harvest (Farooq et al., 2009).

Another issue identified is the uneven distribution of nutrients across the hydroponic pipes. This is attributed to several factors, such as water turbidity disrupting the nutrient absorption of individual plants, and varying nutrient consumption rates due to uneven plant growth stages (e.g., mature and intermediate stages). When nutrients are not evenly distributed, the dynamics of nutrient uptake are disrupted, which can lead to inefficiencies and nutrient losses within the hydroponic system (Vought et al., 2024). Consequently, plants are at an increased risk of experiencing nutrient deficiency, a condition typically characterized by a reduction in shoot and root weight as well as decreased water content in plant tissues. The subsequent impact of this condition is a decline in the quality and yield of the harvest, reflected in suboptimal leaf growth. Without an automated monitoring system, the risk of crop failure increases, particularly during intensive harvest seasons that demand heightened attention to water and nutrient balance. The implementation of smart IoT-based hydroponic systems provides a practical framework for automated agricultural management (Awal et al., 2025; Suresh et al., 2024). More specifically, the integration of real-time monitoring and data retrieval can minimize resource wastage and support more precise nutrient and water management, ultimately maximizing crop yields.

These issues highlight a fundamental weakness in conventional hydroponic monitoring systems, which are primarily descriptive and focus on data presentation without advanced analytical mechanisms. One of the major problems that arises is

diagnostic ambiguity the system's inability to distinguish whether an increase in water turbidity is caused by potentially harmful sediment or by dissolved nutrient concentrations that remain within acceptable limits. This condition can lead to the misinterpretation of water quality and delays in management decision-making. Therefore, hydroponic monitoring systems require a systematic decision support mechanism capable of consistently representing operational knowledge and translating multiple sensor measurements into meaningful operational conditions. Such an approach enables monitoring systems to function not only as data acquisition platforms but also as explainable decision support systems that assist users in making transparent and consistent operational decisions (Tsakiridis et al., 2020).

Various hydroponic monitoring systems have attempted to address this problem by implementing predefined rule-based logic using conventional if-else statements. Although this approach is computationally efficient and straightforward to implement, the resulting decision logic is often embedded directly within the program code, making it difficult to analyse, verify, and maintain as the number of operational rules increases. Furthermore, conventional rule-based implementations generally lack a structured representation that explicitly illustrates the hierarchical relationships among operational conditions, decision paths, and corresponding control actions. In contrast, representing operational knowledge as a decision tree provides a transparent and systematic decision hierarchy, allowing each operational rule to be explicitly documented, verified, and directly translated into an embedded implementation. Consequently, rather than learning decision boundaries solely

from statistical training, integrating scientific and operational knowledge directly into decision tree models can ensure that the resulting representations are both scientifically valid and highly explainable (Sarailidis et al., 2023). Building upon this concept, this study adopts a Knowledge-Driven Decision Tree approach that systematically transforms validated hydroponic operational rules into a structured representation suitable for implementation in an ESP32-based monitoring system.

To address these challenges, this research proposes an Internet of Things (IoT)-based hydroponic monitoring system that integrates real-time sensor monitoring with a Knowledge-Driven Decision Tree for operational decision support. The proposed system combines multiple environmental parameters acquired from water quality sensors with a structured decision hierarchy derived from validated operational knowledge reported in previous hydroponic and water quality studies. Rather than discovering classification patterns through statistical learning, the decision tree serves as a transparent representation of predefined operational rules, enabling the system to evaluate sensor measurements consistently and systematically. This approach allows the monitoring system to transform raw sensor observations into meaningful operational conditions that can be directly interpreted by users and embedded devices.

The hardware architecture consists of an ESP32 Devkit V4 as the primary controller, supported by WEMOS D1 Mini sensor nodes for distributed data acquisition. Sensor measurements are transmitted through the MQTT communication protocol and processed in real time to determine the current operational condition of the hydroponic system. Executing data processing and

decision-making locally at the network edge enables fast, deterministic responses and reduces reliance on heavy cloud-based computation (Shi et al., 2016). Aligning with this edge computing paradigm, the resulting decision hierarchy in this study is subsequently implemented directly on the ESP32 microcontroller as a lightweight hierarchical IF-ELSE structure. This approach enables rapid operational execution without requiring complex statistical model training, parameter optimization, or runtime retraining on the device. Consequently, the proposed approach combines the advantages of IoT-based monitoring with an explainable and computationally efficient decision representation suitable for resource-constrained embedded systems (Prasetyoaji & Anifah, 2025).

The Total Dissolved Solids (TDS) parameter is used to represent the concentration of dissolved nutrients in the hydroponic nutrient solution, expressed in parts per million (ppm). Consequently, variations in TDS values can be used as a direct indicator of nutrient availability for plant growth. In addition, the **turbidity** level is used as an indicator of the physical quality of the water, as an increase in turbidity may indicate the presence of sediment deposits or algal growth that can interfere with nutrient absorption by plant roots. The combination of TDS and turbidity parameters enables a more comprehensive analysis of the nutrient solution condition, particularly in distinguishing changes in water quality caused by variations in nutrient concentration from those resulting from undesirable physical contaminants. To support the stability of water and nutrient distribution throughout the hydroponic piping system, the water flow and water level parameters are also considered operational indicators, as both parameters are directly associated with

the continuity of water supply and the uniformity of nutrient distribution within the hydroponic cultivation system.

In this study, water quality monitoring focuses on two primary parameters: Total Dissolved Solids (TDS) and turbidity. The selection of these parameters is based on their dynamic characteristics and sensitivity to changes in water conditions within hydroponic systems. Previous studies have shown that variations in TDS values reflect fluctuations in the concentration of dissolved ions in the nutrient solution, whereas an increase in turbidity indicates the presence of sediment deposits or algal growth that may hinder nutrient absorption by plant roots (Aziezah et al., 2023). Furthermore, water turbidity acts as a significant physical light-inhibiting factor that affects biological processes such as algal growth (Wang, n.d.). In a hydroponic context, this physical limitation can reduce the overall biological productivity of the system even when nutrient availability is optimal.

Other parameters, such as pH and water temperature, also play important roles in hydroponic plant growth. However, in the hydroponic system used in this study, both parameters remain relatively stable and are manually controlled to maintain the recommended optimal ranges, namely a pH of 6.0-7.0 and a water temperature of 15-30°C (Hermanto et al., 2021; Prabowo et al., 2023). Under these conditions, this study focuses automated monitoring on the parameters that exhibit the highest degree of fluctuation and have the most direct impact on water clarity and nutrient distribution, namely TDS and turbidity. This approach is intended to ensure that the developed monitoring system remains focused on the most operationally relevant

parameters without introducing additional sensor complexity that does not directly contribute to the water quality classification process or the system's automation.

The sensor measurements acquired from the hydroponic monitoring system represent a set of operational parameters describing the current condition of the cultivation environment, including Total Dissolved Solids (TDS1 and TDS2), water turbidity, water level, and nutrient distribution difference (Δ TDS). Since the operational state of a hydroponic system is determined by the interaction among multiple environmental parameters rather than by individual sensor readings, these measurements require a structured evaluation mechanism to ensure consistent interpretation (Cavaliere et al., 2024). Therefore, this research employs a Knowledge-Driven Decision Tree that systematically represents validated decision rules derived from previous scientific studies as a hierarchical decision structure. Instead of learning classification patterns from data, the proposed approach translates established operational knowledge into an explainable decision representation that consistently converts real-time sensor measurements into operational conditions suitable for implementation on embedded IoT devices.

Unlike conventional machine learning applications in which a decision tree is constructed through statistical training, the Decision Tree employed in this research functions as a knowledge representation rather than a predictive learning model. By representing knowledge as a decision tree, systems can provide a transparent decision hierarchy that allows rules to be explicitly documented and verified (Boruah et al., 2022). Applying this concept, the hierarchical tree structure in this study systematically organizes validated hydroponic operational rules into an

explainable sequence of decision paths. This representation simplifies the verification of decision logic, facilitates its translation into a lightweight *IF-ELSE* implementation on the ESP32 microcontroller, and ensures that every automation decision can be directly traced back to its corresponding scientific reference. Integrating explainable artificial intelligence approaches into agricultural IoT systems is essential for providing transparent and understandable operational decision support (Tsakiridis et al., 2020). Guided by this principle, the proposed Knowledge-Driven Decision Tree not only supports real-time operational decision-making but also specifically enhances the transparency and maintainability of the hydroponic monitoring system developed in this study.

Once the operational knowledge has been represented as a hierarchical decision tree, the resulting decision structure is directly embedded into the ESP32 microcontroller to support real-time operational decision making. During system operation, sensor measurements are continuously acquired and evaluated according to the predefined decision hierarchy without performing any statistical inference or model retraining. Each decision path is implemented as a lightweight hierarchical *IF-ELSE* structure that preserves the logical sequence of the validated operational rules. Deploying intelligent algorithms on resource-constrained IoT devices requires careful management of computational overhead, power, and execution speed (Yazici et al., 2018). To address these constraints, the proposed implementation utilizes a lightweight structure that enables deterministic execution, ensuring that every operational decision remains transparent, consistent, and fully traceable to its corresponding decision rule.

The integration of Internet of Things technology with a Knowledge-Driven Decision Tree to establish an explainable operational decision support mechanism for hydroponic monitoring systems. Unlike conventional data-driven approaches that derive decision rules through statistical learning, the proposed method systematically transforms validated operational knowledge reported in previous scientific studies into a transparent hierarchical decision structure suitable for embedded implementation. In modern intelligent systems, preserving the explainability and traceability of a model's reasoning is highly essential to ensure responsible and trusted decision-making (Barredo Arrieta et al., 2020). By applying this principle, the proposed approach enables the consistent interpretation of multiple environmental parameters while maintaining the transparency of every operational decision. Consequently, the proposed system contributes not only to real-time hydroponic monitoring but also to the development of systematic knowledge representation techniques for resource-constrained IoT-based decision support systems.

In terms of the monitoring aspect, this study utilizes a Telegram Bot platform as the user interface to display real-time sensor monitoring data. The Telegram Bot is used to present information regarding the condition of the hydroponic system and to provide notifications whenever specific conditions are detected, such as deteriorating water quality or nutrient deficiencies. In addition to supporting the automation system, the Telegram Bot also provides manual control functionality as a complementary mechanism, enabling users to monitor and respond to system conditions more promptly based on the information presented.

Based on the identified challenges and research gaps, this study proposes the implementation of an Internet of Things (IoT) based hydroponic monitoring system using a Knowledge-Driven Decision Tree for operational decision support. The proposed approach combines real-time environmental monitoring with a structured decision representation derived from validated operational knowledge reported in previous scientific studies (Brachman et al., n.d.). IoT-based platforms have proven to be highly effective in facilitating precision irrigation and smart water management in modern agriculture (Kamieniski et al., 2019). To achieve this within the proposed ESP32-based embedded system, a Decision Tree is employed as an explainable knowledge representation that systematically organizes operational rules into a transparent hierarchical structure, rather than relying on statistical learning to generate decision rules. By deploying intelligent processing at the edge, systems can achieve more efficient and autonomous decision-making in resource-constrained IoT environments (Zhou et al., 2019). Building on this edge computing paradigm, the developed system is expected to provide consistent interpretation of multiple water quality parameters, support systematic operational decision-making, and contribute to the development of explainable knowledge-based decision support systems in hydroponic cultivation.

1.2. Problem Identification

Based on the background described above, the problems identified in this study are as follows:

- 1.2.1. Water quality in the hydroponic system has not been comprehensively monitored, particularly in distinguishing turbidity caused by sediment

deposits from that caused by dissolved nutrient concentrations, resulting in ambiguity when interpreting water quality conditions.

1.2.2. Water availability within the hydroponic piping system has not been adequately monitored, often causing some plants to experience water shortages, which negatively affects crop yield.

1.2.3. Nutrient distribution within the hydroponic nutrient solution has not been optimized, as indicated by imbalances in nutrient concentration, resulting in some plants receiving nutrient levels that do not meet their optimal requirements.

1.2.4. Water flow in the hydroponic system has not been adequately monitored, making it difficult to detect pipe blockages or leaks in the irrigation piping or pump.

1.2.5. Communication among system components, including sensors, microcontrollers, and the cloud server, has not yet adopted the Message Queuing Telemetry Transport (MQTT) protocol, which can improve the efficiency and speed of data transmission in IoT monitoring systems.

1.3. Research Questions

Based on the problem identification described above, the research questions of this study are as follows:

1.3.1. How can an IoT-based monitoring and automation system be designed to monitor water clarity, water availability, water flow, and nutrient distribution within the hydroponic piping system in real time?

- 1.3.2. How can a Knowledge-Driven Decision Tree be represented and integrated into the ESP32 microcontroller to interpret real-time sensor measurements and generate operational decisions for hydroponic water quality management?
- 1.3.3. How can data communication among ESP32 devices be integrated using the Message Queuing Telemetry Transport (MQTT) protocol, while connecting the system to cloud storage and displaying the monitoring data through a Telegram Bot?
- 1.3.4. To what extent is the proposed monitoring and automation system consistent and reliable in supporting hydroponic operational decision-making?

1.4. Research Limitations

Based on the problem statement, the scope of this study is limited as follows:

- 1.4.1. This study focuses on the development of an IoT-based hydroponic monitoring and automation system that includes monitoring of water turbidity, nutrient distribution, water flow rate, and water availability within the hydroponic system.
- 1.4.2. Water quality and nutrient monitoring are conducted using a limited number of sensors and measurement points. Therefore, the monitoring results represent the system conditions only partially and do not individually cover all hydroponic pipelines.
- 1.4.3. The confidence of the turbidity-cause classification (nutrient versus non-nutrient) in this study is based on an indirect inference derived from

literature rather than direct verification of the turbidity source. Consequently, the system cannot distinguish between different non-nutrient causes of turbidity such as suspended sediment, algae, or other pollutants as these are grouped under a single non-nutrient classification.

1.4.4. The study employs a Knowledge-Driven Decision Tree constructed from validated operational rules reported in previous scientific studies. The decision structure is implemented directly on the ESP32 microcontroller without performing statistical model training or adaptive learning during system development or operation.

1.4.5. The operational decision rules employed in this research were derived from validated findings reported in previous scientific literature. The independent development of an expert-validated knowledge base or ground truth through expert elicitation and field validation was beyond the scope of this study.

1.4.6. The proposed decision hierarchy represents operational knowledge obtained from the selected literature included in this study. Consequently, the resulting decision structure is intended to support hydroponic operational decision making within the defined environmental conditions and should not be generalized to different hydroponic configurations without further validation.

1.4.7. The IoT system developed in this study is designed to operate with an active Internet connection and does not include an operating mechanism for offline conditions.

- 1.4.8. Regarding automation, this study is limited to two automated actions: water drainage and water replenishment (irrigation). For all other conditions, the system provides monitoring and notifications based on the measured water quality parameters
- 1.4.9. This study is conducted using only one type of plant, namely pakcoy (*Brassica rapa* L.), cultivated in a hydroponic system based on the Deep Flow Technique (DFT).

1.5. Research Objectives

Based on the problems described above, the objectives of this study are as follows:

- 1.5.1. To design an IoT-based hydroponic monitoring and automation system for water quality by utilizing water turbidity, nutrient concentration, water level, and water flow as monitoring parameters to support real-time operational decision-making in hydroponic system management.
- 1.5.2. To develop a Knowledge-Driven Decision Tree by representing validated operational rules derived from previous scientific studies and to implement the resulting decision structure on the ESP32 microcontroller for real-time hydroponic operational water quality monitoring.
- 1.5.3. To implement the Message Queuing Telemetry Transport (MQTT) communication protocol to enable data communication among devices in the IoT system, store real-time data in a cloud database, and present monitoring and automation results through a Telegram Bot

- 1.5.4. To verify the consistency of the proposed decision-making mechanism against operational sensor data collected from the implemented system.

1.6. Research Significances

Based on the research objectives described above, this study is expected to provide both theoretical and practical contributions, as outlined below.

1.6.1. Theoretical Significances

- 1.6.1.1. To enrich knowledge and provide references for the development of IoT-based hydroponic monitoring systems, particularly through the integration of real-time sensing and knowledge-driven operational decision support for water quality management.
- 1.6.1.2. To contribute to the development of more transparent and explainable hydroponic monitoring methods through the integration of sensors and data communication using the Message Queuing Telemetry Transport (MQTT) protocol, and embedded operational decision support.
- 1.6.1.3. To expand the academic literature in the field of smart agriculture through the application of Internet of Things (IoT) and Knowledge-Driven Decision Tree-based operational decision support.

1.6.2. Practical Significances

- 1.6.2.1. To assist hydroponic farmers in monitoring water quality conditions and supporting operational decision making based on real-time sensor information..
- 1.6.2.2. To support early identification of nutrient imbalance, excessive turbidity, and low water level conditions that may affect hydroponic

system operation.

1.6.2.3. To serve as a reference for future research and development of IoT-based hydroponic monitoring systems utilizing knowledge-driven operational decision support.

1.6.2.4. To provide Dago Engineering with a reference implementation of an IoT-based hydroponic monitoring system integrating real-time sensing and a Knowledge-Driven Decision Tree for operational decision support, which can support future research and development activities, prototype refinement, and the development of intelligent hydroponic monitoring solutions tailored to industrial requirements.

