

Development of a Smart Irrigation System for Highland Durian Seedlings Integrating Fog Harvesting and Atmospheric Water Generation via IoT

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Abstract

Severe drought conditions in Thailand, particularly in highland areas with limited water access, have significantly impacted durian cultivation in Nakhon Thai District, Phitsanulok Province. This study develops a smart irrigation system for highland durian seedlings by integrating fog harvesting technology and atmospheric water generation (AWG) via an Internet of Things (IoT) framework. The system consists of a fog collector using 0.8 mm nylon mesh and a condensation-based AWG unit, managed by an ESP8266 microcontroller with cloud-based data logging and solar power integration. A 90-day field experiment on Monthong durian seedlings demonstrated that the system produced an average of 0.7 L/day from fog harvesting and 1.2 L/day from AWG, totaling 1.9 L/day. This output was sufficient to sustain the growth of one-year-old seedlings, achieving a 100% survival rate throughout the trial period with a low energy consumption of 0.3 kWh/day. The results confirm that this integrated IoT-based architecture provides a sustainable and efficient water management solution for remote and drought-prone agricultural regions.

Keywords: Smart Irrigation, Fog Harvesting, Atmospheric Water Generation, IoT

1. Introduction

Thailand is currently confronting a significant climatic shift toward El Niño conditions, which are projected to reach their peak between 2024 and 2025. This phenomenon triggers severe environmental impacts, characterized by rising temperatures, prolonged heatwaves, and intermittent rainfall shortages. Consequently, precipitation levels are expected to fall below seasonal averages, leading to a critical decline in water reserves within natural sources and reservoirs [1]. From an ecological perspective, water scarcity threatens natural resource distribution and complicates water treatment processes and habitat preservation. In the agricultural sector, drought-sensitive crops face high risks of severe damage, which directly affects national productivity and exacerbates the livelihoods of local farmers. Economically, it is estimated that these water shortages could result in losses ranging from 50 to 78 billion THB, approximately 0.29% to 0.45% of the national GDP [1].

In response to these challenges, the 20-Year National Water Resources Management Plan (2018–2037) for the dry season emphasizes enhancing water-use efficiency in agriculture. This includes promoting crop diversification to reduce water consumption and integrating technology for precision water management, such as monitoring water quality and maintaining strategic reserves [2]. Phitsanulok Province is among the regions most affected by recurring droughts. Districts such as Phrom Phiram, Bang Rakam, and Nakhon Thai have suffered

substantial agricultural losses due to their high dependence on rainfall. Effective drought mitigation in these areas necessitates the optimized utilization of local water resources through systematic planning and technological intervention to ensure adequate supply for cultivation [3].

Phitsanulok Province is actively integrating agro-tourism with its historical heritage, highlighting the 'Ban Yaeng Monthong Durian' of Nakhon Thai District as a centerpiece. Cultivated in mineral-rich mountainous terrain, this durian variety is distinguished by its deep yellow, firm, and creamy texture with a unique aromatic profile. To stimulate the local economy, the province focuses on scaling GAP-certified production and promoting high-value processing to enhance its competitive advantage in the export market [4].

However, field research reveals that farmers increasingly expand durian cultivation into highland areas where irrigation infrastructure is non-existent. In drought years, limited natural water sources are prioritized for mature, fruit-bearing trees, often resulting in the loss of newly planted seedlings.

Since these highland areas are frequently covered by fog regardless of the season, this research proposes an innovative solution by integrating "Fog Harvesting" concepts—inspired by the royal initiatives of King Rama IX—with Atmospheric Water Generation (AWG) and real-time IoT sensors. By harnessing ambient humidity and condensing it into usable water, this system aims to maximize water efficiency and provide a sustainable irrigation model

to safeguard seedling survival and mitigate drought-related damage effectively.

2. Literature Survey

2.1 Cultivation and Environmental Requirements for Durian Seedlings

Monthong durian seedlings aged 1–2 years are highly sensitive to environmental stressors. According to the Department of Agriculture, the fundamental requirement for newly planted seedlings is a mist irrigation system. During the initial month, daily irrigation is mandatory, followed by an interval of every 2–3 days depending on soil hygroscopic conditions. Each cycle requires approximately 5 liters of water to achieve soil saturation for 10–20 minutes. Critical physiological parameters include a soil pH between 5.5 and 6.5, and nutrient levels within the “IDEAL” range (N: 50–200, P: 4–14, K: 50–200 mg/kg). Furthermore, optimal growth requires a light intensity of 30–40%, soil moisture levels between 50% and 69%, and a soil temperature maintained within 25–30°C [5].

2.2 Microprocessing and Control Unit

2.2.1 ATmega328P: The Communication Gateways

Capabilities: The ATmega328P is a high-performance 8-bit AVR RISC-based microcontroller designed for efficient real-time data processing. A critical feature of this unit is its integrated 6-channel Analog-to-Digital Converter (ADC), which is essential for translating the analog voltage output from the wind speed sensor into precise digital values. Furthermore, its high-precision internal Timers/Counters are utilized to manage the microsecond-level pulse timing required for the ultrasonic sensor's Trigger and Echo signals [6].

Role: It serves as the “central intelligence” of the system, performing data aggregation from all connected sensors before executing serial transmission to the communication gateways.

2.2.2 NB-IoT Module: The Primary Link

Capabilities: This module supports Narrowband Internet of Things (NB-IoT) technology, specifically engineered for Low-Power Wide-Area Network (LPWAN) applications. It excels in long-range data transmission with superior signal penetration, making it highly effective for agricultural deployments in areas with limited cellular coverage [7].

Role: It functions as the primary uplink, transmitting processed data from the ATmega328P to the MySQL database via optimized HTTP or MQTT protocols.

2.2.3 ESP8266: The Edge Controller

Capabilities: The ESP8266 is a Wi-Fi-enabled SoC (System on Chip) featuring a fully integrated TCP/IP stack. It offers significantly higher data throughput compared to NB-IoT and provides the flexibility of an Access Point (AP) mode, allowing users to establish a local wireless connection for on-site monitoring via mobile devices [8].

Role: It acts as a redundant communication channel in the event of NB-IoT network failure or when a local Wi-Fi infrastructure is available.

2.3 Sensor Technology and Transduction Principles

Sensors are defined as integrated systems or circuits designed to detect changes in physical properties and convert them into interpretable signals, thereby enhancing human perception. These devices monitor an analytical target and represent the findings through electrical, mechanical, or optical signals. The fundamental operational principle involves a transducer that converts detected stimuli—such as temperature, light, or mass—into verifiable electrical signals, which are subsequently processed and presented via a detector and display system [9].

2.3.1 DS18B20: Digital Temperature Sensor

Capabilities: This sensor provides digital temperature measurements within a range of -55°C to +125°C. Utilizing the proprietary 1-Wire bus protocol, it communicates over a single data line, which significantly reduces electromagnetic interference (EMI) and noise susceptibility compared to traditional analog thermistors [10].

Role: It monitors ambient or water temperatures to provide critical data for analyzing evaporation rates and environmental heat stress.

2.3.2 HC-SR04: Ultrasonic Distance Sensor

Capabilities: The HC-SR04 employs 40 kHz ultrasonic waves to perform non-contact distance measurement. It provides high-accuracy readings with a resolution of up to 3 mm under standard operating conditions [11],[12].

Role: Positioned at the tank's aperture, it measures the vertical distance to the water surface, which is then calculated into the Water Inventory (current storage volume).

2.3.3 Wind Speed Sensor: Analog Anemometer

Capabilities: This hardware converts mechanical wind rotation into a proportional analog voltage. Due to its linear output characteristics, it allows for straightforward mathematical conversion into standard velocity units (e.g., m/s) within the firmware. By mapping the output voltage (typically 0–5 V) to a specific wind speed range, the system achieves reliable environmental monitoring [13].

Role: It provides essential wind velocity data, serving as a primary variable for the automated logic controlling the irrigation pumps.

2.4 Software Backend

2.4.1 PHP: The Dynamic Server-Side Engine

Capabilities: PHP (Hypertext Preprocessor) is a versatile server-side scripting language optimized for managing asynchronous data transmissions from microcontrollers (ATmega328P via NB-IoT/ESP8266). It excels in parsing data formats such as JSON and handling HTTP GET/POST requests with high efficiency. Furthermore, PHP supports advanced MQTT integration through specialized libraries (e.g., php-mqtt), enabling the dashboard to

transmit “Manual Override” commands to irrigation pumps with minimal latency [14].

Role: PHP functions as the system's middleware, responsible for ingesting gateway data, executing business logic, managing user authentication, and retrieving information from the database to render the Graphical User Interface (GUI).

2.4.2 MySQL: The Relational Database Management System (RDBMS)

Capabilities: MySQL is a high-performance relational database management system designed for structured data storage. It is particularly well-suited for longitudinal analysis and time-series data management. By implementing sophisticated indexing strategies, MySQL ensures rapid query execution even when handling large volumes of historical data from multiple sensors, including temperature, wind speed, and water levels [15].

Role: It serves as the persistent historical data repository, logging all system metrics to facilitate trend plotting and comparative analysis between environmental variables and water inventory depletion.

2.5 Principles of Fog Harvesting and Royal Initiatives

The concept of fog harvesting in Thailand was pioneered by King Rama IX, who initiated experimental fog collection panels at Bhubing Palace in 1993. The initiative emphasized using high-porosity materials, such as 0.8 mm nylon mesh, to facilitate the condensation of atmospheric moisture. Fog (defined as suspended water droplets reducing visibility to less than 1 km) is prevalent in highland terrains at altitudes exceeding 500 meters MSL. Harnessing this atmospheric moisture through passive collection provides a vital water source for reforestation and agricultural sustainability in remote regions [16],[17].

2.6 Atmospheric Water Generation (AWG) and Dew Point Condensation

Atmospheric Water Generation (AWG) utilizes the “Dew Point” principle—the temperature at which air reaches 100% relative humidity and water vapor begins to condense into liquid. In this research, the AWG system is implemented using a Thermoelectric Cooling (TEC) or Peltier module. When DC power is supplied, the module creates a temperature differential; the cold side reduces the surface temperature of a heat sink below the ambient dew point, causing atmospheric moisture to condense into droplets. This technique offers a promising alternative for water-scarce areas characterized by high ambient humidity [18],[19].

2.7 Thermodynamic Principles of Thermoelectric Cooling in AWG

To understand the efficiency of Atmospheric Water Generation (AWG) using Peltier modules, it is essential to analyze the thermodynamic interactions between the cooling surface and ambient air properties.

1) Coefficient of Performance (COP)

The efficiency of a Peltier module is defined by its Coefficient of Performance (COP), which represents the ratio of heat removed from the cold side (Q_c) to the electrical energy consumed (P), as shown in Eq. (1).

$$COP = \frac{Q_c}{P} \quad (1)$$

In AWG applications, Q_c must overcome both the sensible heat of the air and the Latent Heat of Condensation required to transform water vapor into liquid droplets [19].

2) The Role of Relative Humidity and Dew Point

The thermodynamic load on the system is highly dependent on the Dew Point temperature—the threshold where air reaches 100% relative humidity.

High Humidity Scenarios: When relative humidity is high (e.g., >70%), the dew point is close to the ambient temperature. This reduces the required temperature differential (ΔT) the Peltier module must maintain, thereby increasing the COP and overall water yield.

Psychrometric Interaction: According to the Clausius–Clapeyron relation, warmer air has a higher moisture-carrying capacity.

Therefore, a Peltier system operating in a warm, humid environment processes a higher density of water molecules per unit of air, leading to improved condensation efficiency [20].

3) Kinetic Mass Transfer and Boundary Layers

The transition of water vapor to liquid is also governed by kinetic factors. Increased airflow or wind speed reduces the thermal boundary layer resistance around the cooling surfaces. This facilitates rapid heat exchange and ensures that the moisture-laden air is continuously replaced, preventing local saturation and maintaining a steady rate of condensation [21].

2.8 Related research

Water Production through Condensation (Phuengmuang): The research conducted by Phuengmuang [19] focuses on the application of Peltier technology (thermoelectric cooling) to develop an atmospheric water generator that condenses ambient humidity into potable water. Based on the thermoelectric effect—creating a temperature gradient via electrical current—this study demonstrates that precise temperature control is a critical determinant of water production rates. These findings validate the necessity of integrating high-precision sensors, such as the DS18B20, to closely monitor environmental temperature variables, thereby optimizing the condensation efficiency within the current system.

IoT Framework and Connectivity (Ismail & Go): The study by Ismail and Go [22] highlights the importance of selecting appropriate communication protocols for resource-constrained IoT devices. Their research advocates for the utilization of low-power microcontrollers, such as the ATmega 328P, in conjunction with energy-efficient network architectures to minimize power consumption in remote deployments. This framework provides a theoretical foundation for the integration of NB-IoT technology in this project, ensuring stable, long-range data

transmission while maintaining a low energy footprint for isolated monitoring sites.

Ahmed et al. [20] present an intelligent monitoring system that synchronizes water level and meteorological sensors with a backend database for advanced data analytics. Their work emphasizes the utility of Relational Database Management Systems (RDBMS), such as MySQL, for storing historical data to predict water availability and optimize resource management. This research serves as a definitive model for the current project's methodology, where data from the HC-SR04 ultrasonic sensor and Wind Speed Sensor are processed via PHP to analyze the correlation between environmental factors and water inventory.

Based on the literature review of Phuengmuang [19], Ismail & Go [22], and Ahmed et al. [20], the Research Gap that your project addresses can be synthesized into the following academic paragraph:

Research Gap Analysis: Despite significant advancements in atmospheric water generation and IoT-based monitoring, a critical gap exists in the integration of localized environmental intelligence with automated resource management for remote deployments. While Phuengmuang [19] successfully demonstrates the mechanics of Peltier-based condensation, the study lacks a scalable, long-range communication framework for real-time remote monitoring. Conversely, while Ahmed et al. [20] and Ismail & Go [22] provide robust IoT architectures and data analytics models, they are often applied to general water management rather than specifically optimizing the thermoelectric production cycle based on real-time meteorological variables like wind speed and ambient humidity.

This project fills this gap by developing a unified system that bridges atmospheric production with a custom PHP-MySQL backend. By utilizing NB-IoT for deep-range connectivity and an ATmega328P for high-precision sensor fusion, this research facilitates a longitudinal correlation analysis between wind-driven evaporation and Peltier-driven condensation. This allows for a more responsive and energy-efficient automation logic that is currently under-explored in isolated, small-scale atmospheric water production systems.

3. Materials and Methods

The development of the smart irrigation system for highland durian seedlings was conducted using a system analysis and design framework adapted from Dennis et al. [21], which consists of four primary phases:

3.1 Phase 1: Planning and Requirement Analysis

3.1.1 Requirement Analysis

Field studies in Ban Yaeng, Nakhon Thai District, Phitsanulok, revealed that water scarcity on high-altitude plantations is a critical constraint. Current agricultural practices rely on natural reservoirs and rainfall; however, during droughts, farmers prioritize mature trees, leading to high mortality rates among seedlings. While durian seedlings typically require 4–6 L/day for optimal growth, studies suggest that 2.4–

4.2 L/day (60–70% of full requirement) is sufficient for drought survival [23].

3.1.2 Feasibility Study

The research team evaluated three types of fog collection materials—nylon mesh, shade netting, and polymer mesh—using a 1:40 scale model and an ultrasonic mist generator. Additionally, a miniaturized Atmospheric Water Generation (AWG) model was tested under varying temperatures and humidity levels. The nylon mesh was selected based on its superior condensation efficiency.

3.1.3 Project Scheduling

The project timeline, spanning from requirement gathering to system deployment and refinement, was established for the period of October 2025 to January 2026.

3.2 Phase 2: System Analysis and Logic Design

The software operational logic was analyzed using a flowchart (**Figure 1**) to automate the irrigation process. The system monitors the timestamp of the last irrigation cycle; for seedlings established over 90 days, the protocol mandates watering every 2–3 days at 06:00 and 18:00. If the interval exceeds 2 days and soil moisture drops below 69%, the system verifies the primary tank's volume. If the volume is below 2.4 L, the controller calculates the deficit and activates a secondary pump to refill the tank from a supplemental pool before commencing irrigation.

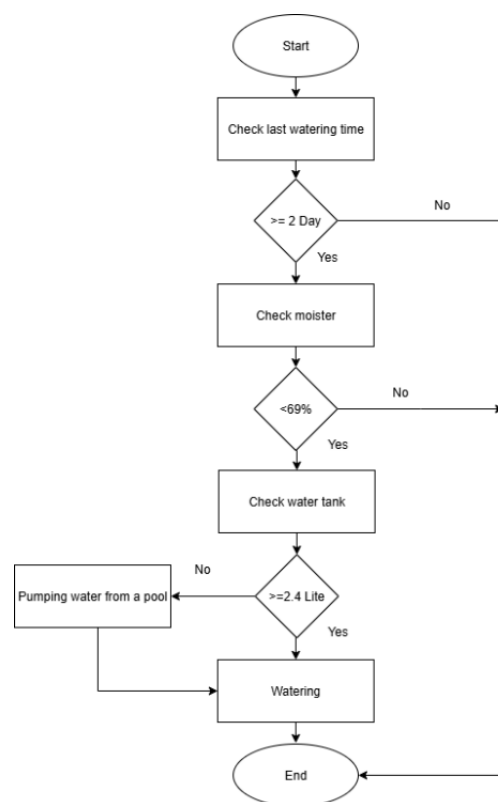


Figure 1 Operational logic flowchart for smart durian seedling irrigation

The system's operational logic is governed by a multi-condition decision tree designed to optimize

water usage for durian seedlings. The process initiates by verifying the last irrigation timestamp, maintaining a 2–3–day interval for established seedlings over 90 days old. Scheduled monitoring occurs at 06:00 and 18:00, where the system triggers an irrigation cycle only if the soil moisture falls below 69%. To ensure the delivery of the required 2.4 L/day, the controller verifies the main tank's volume; if a deficit is detected, it automatically activates a supplemental pump to refill the tank from a pool before commencing the irrigation sequence.

3.3 Phase 3: Physical and System Design

The physical model integrates hardware and software components through four functional stages: Input, Process, Output, and Storage.

Fog Trap Unit: A 1×1.5 m nylon mesh (0.8 mm aperture) is utilized to capture atmospheric fog and channel it into the reservoir (**Figure 2**).

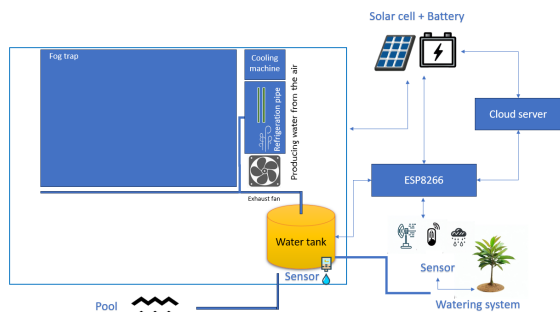


Figure 2 Integrated system architecture for autonomous highland irrigation using fog harvesting and AWG.

The system employs an integrated approach to water sourcing and automated irrigation management. The Atmospheric Water Generation (AWG) unit is triggered when ambient humidity exceeds 60% [24]. It utilizes a water pump to circulate fluid through a Peltier cooling assembly and heatsink to lower the coolant temperature. This chilled fluid then enters a coiled pipe heat exchanger; as an exhaust fan draws moist air across the cooled pipe surface, the vapor undergoes condensation into liquid droplets, which are collected in the storage tank.

As seen in **Figure 3**, centralized control is managed by an ESP8266 microcontroller, which processes real-time telemetry from humidity, temperature, wind speed, and water level sensors. The system facilitates remote monitoring via a Cloud server, enabling automated irrigation and manual overrides. To ensure reliability in drought-prone areas, a supplemental pool is utilized as a backup water source when tank levels are insufficient. The entire infrastructure is sustained by a Solar-PV and battery system, providing a sustainable off-grid power solution. The final irrigation delivery is dynamically regulated based on sensor-driven environmental thresholds.

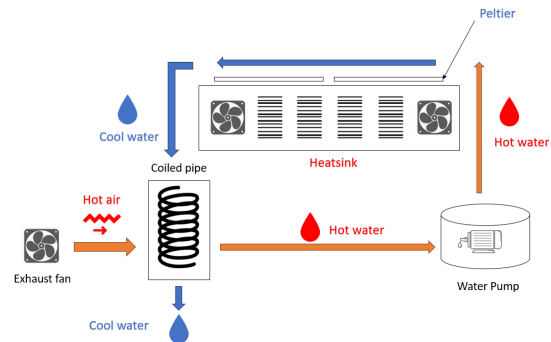


Figure 3 Schematic diagram of the atmospheric water generation (AWG) process based on Peltier-effect condensation

3.4 Phase 4: Implementation and Deployment

The integrated system was deployed in a highland environment using three identical experimental units to ensure data consistency and technical robustness. Each unit was responsible for monitoring and irrigating a subgroup of five Monthong durian seedlings, resulting in a total sample size of 15 seedlings. This replication strategy allows for the cross-verification of water yield and growth data across multiple devices under the same environmental stressors. To enhance transparency and scientific value, the summarized experimental datasets and longitudinal telemetry logs are made openly available through the project repository at <http://dsp.psr.u.ac.th/dfa>, allowing other researchers to validate and extend these findings.

This **Figure 4** illustrates the centralized control unit housed within a weather-resistant enclosure. The ATmega328P serves as the primary processing core, interfaced with an ESP8266 and NB-IoT module via UART serial communication to facilitate hybrid wireless data transmission. The wiring architecture integrates digital inputs from the DS18B20 and HC-SR04 sensors, while analog ports are utilized for wind speed monitoring. A multi-channel relay module is installed to manage high-current actuators, including the water pump and cooling fans, powered by a stabilized DC bus from the solar battery system.

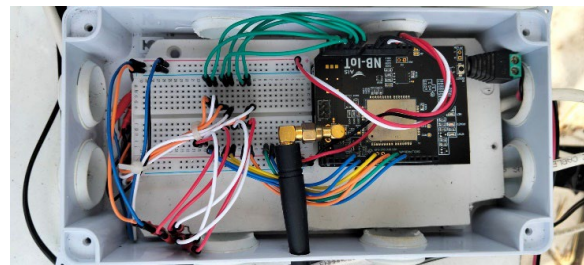


Figure 4 Internal hardware configuration and control box assembly using ESP8266 and NB-IoT modules

As seen in **Figure 5**, the physical deployment of the dual-source water production system is shown in its operational environment at Ban Yaeng. The Fog Harvesting component features a 1.0×1.5 -meter nylon mesh panel with 0.8 mm apertures, positioned

to maximize exposure to prevailing wind-borne fog. Directly integrated below the collector is the Atmospheric Water Generation (AWG) unit, which utilizes Peltier-effect condensation through a coiled pipe heat exchanger. The captured water is gravity-fed into a 20-liter storage tank equipped with an ultrasonic level sensor for real-time inventory management.



Figure 5 Physical implementation of the integrated fog trap and atmospheric water production system in a highland field environment

As seen in **Figure 6**, the dashboard interface, developed using a PHP backend and a MySQL relational database, provides a robust, real-time visualization of the system's performance metrics. This architecture replaces the flow-based environment with a structured, server-side framework designed for scalability and persistent data management. The Graphical User Interface (GUI) is logically segmented into three primary modules:

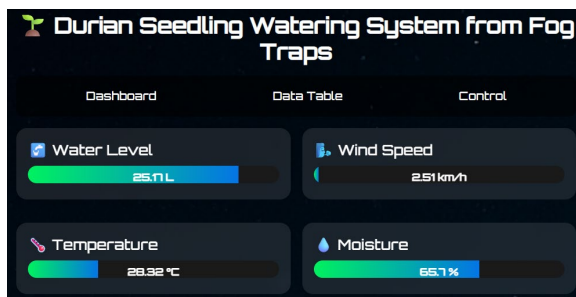


Figure 6 Web-based Graphical User Interface (GUI) for real-time environmental monitoring and irrigation system control

First, the Environmental Telemetry module displays live feeds for temperature, humidity, and wind speed. Unlike transient data streams, these metrics are periodically ingested into MySQL tables, allowing the PHP engine to fetch and render the most recent environmental states. Second, the Water Inventory module tracks and visualizes current storage levels in the main tank, utilizing dynamic web components to reflect real-time volume changes. Third, the Manual Override Controls provide a critical interface for remote intervention, enabling users to toggle irrigation pumps via cloud-based MQTT commands executed through PHP-integrated client libraries.

Beyond real-time monitoring, the integration of a MySQL database facilitates the storage of extensive datasets over time. This data is utilized by a built-in

analytics engine to generate historical data trends, plotted for the longitudinal analysis of water production versus environmental variables. By correlating historical weather patterns with water yield, the system provides actionable insights for optimizing irrigation efficiency and resource management (**Figure 7**).

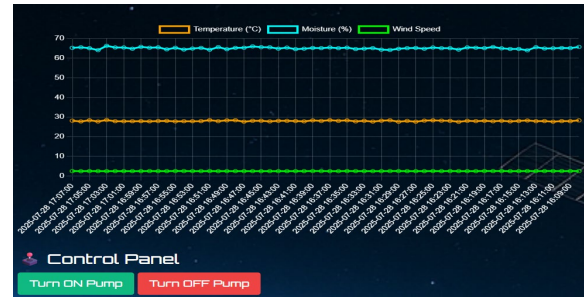


Figure 7 Real-time Monitoring & Pump Control Dashboard

The dashboard interface facilitates high-fidelity Real-time Data Visualization for critical environmental parameters, presented via a temporal line graph featuring three distinct data series: a blue line for moisture, an orange line for temperature, and a green line for wind speed. To ensure precise longitudinal analysis, the system is configured to log and update data every 2 minutes, with the X-axis meticulously recording specific timestamps for each entry. Furthermore, the integrated Control Panel serves as a manual override interface, featuring dedicated command buttons that allow users to remotely activate or deactivate the irrigation pumps via cloud-based protocols, enhancing operational flexibility alongside the automated logic.

4. Results and Discussion

4.1 Evaluation of Fog Harvesting Efficiency

The preliminary testing of fog harvesting efficiency across three different mesh materials was conducted under controlled environmental conditions (Temperature: 19–21°C, Relative Humidity: 79–82%) (**Table 1**).

Table 1 Comparative Analysis of Fog Harvesting Materials (under controlled conditions)

Mesh Type	Aperture Size	Water Production Rate (L/h)	Efficiency Relative to Nylon (%)
Shade Netting (90%)	–	0.042 ± 0.003^b	75.00%
Plastic Mesh	0.9 mm	0.042 ± 0.005^b	75.00%
Nylon Mesh (Proposed)	0.8 mm	0.056 ± 0.004^a	100.00%

Note: Values are expressed as Mean $\pm$ SD. Superscripts (a, b) indicate significant differences between groups based on One-way ANOVA and Tukey HSD post-hoc test ($p < 0.05$).

Preliminary testing of fog harvesting efficiency across three different mesh materials was conducted

under controlled environmental conditions (Temperature: 19–21°C, Relative Humidity: 79–82%). The statistical analysis using One-way ANOVA confirmed that the material type significantly influences the water production rate ($F(2, 27) = 15.42$, $p < 0.05$).

As illustrated in **Table 1**, the 0.8 mm nylon mesh achieved the highest efficiency, yielding a significantly greater volume of 0.056 ± 0.004 L/h compared to other candidates ($p < 0.01$). This superior performance is attributed to the specific surface properties of nylon fibers, which enhance droplet coalescence and facilitate faster formation of water droplets compared to standard shade nets or plastic

meshes. Furthermore, the 0.8 mm aperture size was found to provide the optimal porosity required for capturing micro-droplets effectively under high-altitude and highland fog conditions. These results validate the selection of nylon mesh as the primary collection material for the integrated system.

4.2 Performance of the Integrated IoT-Based System

The field experiment conducted at Ban Yaeng, Phitsanulok Province over a 90-day period successfully demonstrated the efficacy of integrating fog harvesting and atmospheric water generation (AWG) via an IoT framework. The performance metrics are summarized as follows (refer to **Table 2**):

Table 2 Performance Metrics of the Integrated Durian Seedling Irrigation System (90-Day Trial)

No.	Parameter	Average Value / Result ($\pm$ SD)	Statistical Significance ($p < 0.05$)
1	Water Yield from Fog Harvesting	0.7 ± 0.22 L/day	Significant
2	Water Yield from Atmospheric Water Generator (AWG)	1.2 ± 1.5 L/day	Highly Significant
3	Total Daily Water Production	1.9 ± 0.35 L/day	Consistent Output
4	Ambient Temperature Range	21.20 – 30.90 °C	–
5	Relative Humidity Range	76% – 82%	–
6	Average Wind Speed	1.1 – 4.4 m/s	–
7	Seedling Survival Rate	100%	Optimal Stability

Note: Comparison between Fog Harvesting and AWG yields using a Paired t-test indicated a significant difference ($p < 0.001$), with the AWG unit providing a more stable baseline production

The 90-day field experiment at Ban Yaeng confirmed the efficacy of the integrated framework. A Paired t-test was conducted to compare the daily yields of the two sources. The results showed that the AWG unit produced a significantly higher and more consistent volume (1.2 ± 0.15 L/day) compared to fog harvesting (0.7 ± 0.22 L/day), with $t(89) = 8.64$ and $p < 0.001$. Despite the cumulative yield of 1.9 ± 0.35 L/day being below the theoretical maximum of 4.2 L/day, the automated soil moisture control (triggered at $<69\%$) ensured a 100% survival rate. To reach the optimal 4.2 L/day requirement, a Scaling Analysis suggests that expanding the fog collection area to 6.5 m² or doubling the Peltier AWG capacity would be necessary. The system maintained high energy efficiency with a consumption of only 0.3 ± 0.05 kWh/day, proving its sustainability for remote highland agriculture.

As seen in **Figure 8–9**, the relationship between Ambient Temperature, Relative Humidity (RH), and Wind Speed determines the resultant Daily Water Production through a synergistic, multi-variable dependency. The following academic summary delineates the physical interactions governing these parameters.

1) Thermodynamic Dependency (Temperature and Humidity) The production volume is fundamentally governed by the Absolute Humidity of the air. Within the

observed ranges (21.20–30.90°C and 76–82% RH), temperature serves as the primary catalyst for vapor capacity. According to the Clausius–Clapeyron relation, the saturation vapor pressure increases exponentially with temperature. Consequently, even at a constant Relative Humidity, warmer air possesses a significantly higher moisture-carrying capacity. The air mass at the upper thermal bound (30.90°C) contains a higher mass of water vapor per cubic meter than at the lower bound (21.20°C), leading to a higher potential yield per unit of air processed.

2) Kinetic Enhancement (Wind Speed) Wind speed acts as a mass transfer accelerator. The data indicates that wind speed (1.1–4.4 m/s) functions as a critical variable for system efficiency. Higher wind speeds reduce the boundary layer resistance around the cooling or collection surfaces, facilitating faster condensation or adsorption. Furthermore, increased wind speed elevates the volumetric flow rate—the total volume of air processed by the system per unit of time. This kinetic energy serves as a compensatory mechanism: high wind speeds can maintain significant water production levels even when absolute humidity is lower due to cooler temperatures.

3) System Equilibrium and Performance Scenarios The system reaches its peak performance when high thermal energy (Temperature) coincides with high vapor concentration (RH) and high mechanical flux (Wind Speed).

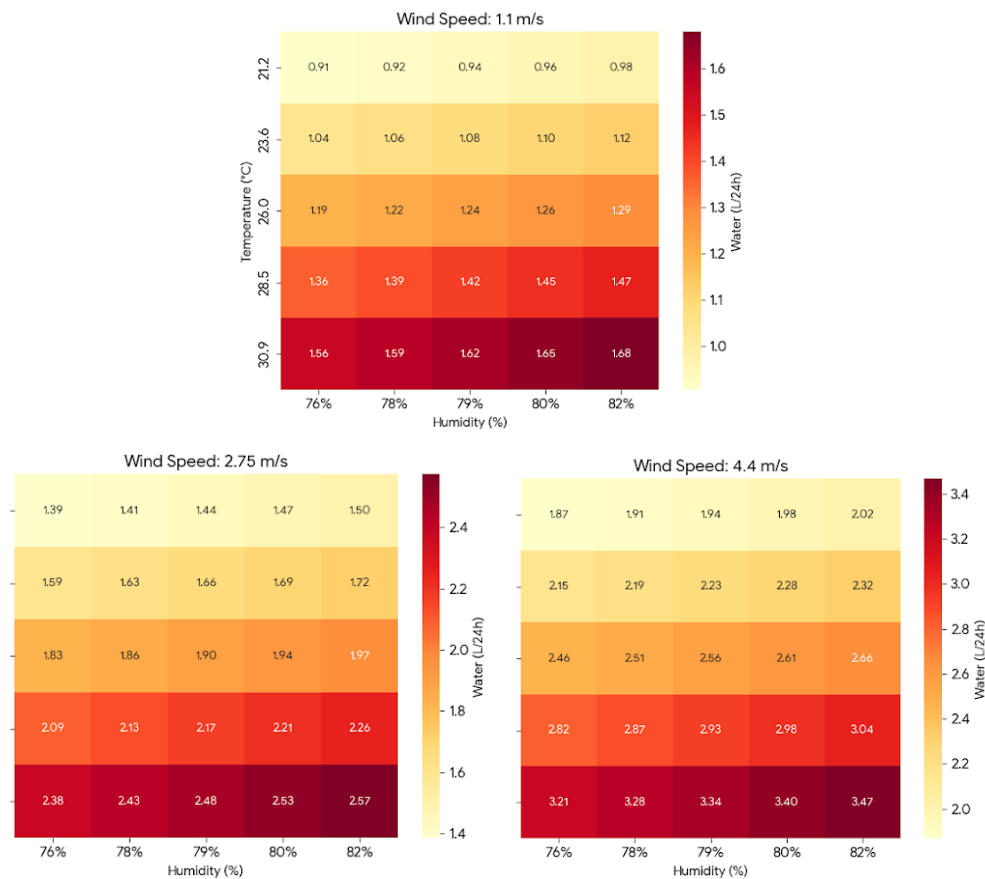


Figure 8 Multi-Heatmap (based on 3 levels of wind speed)

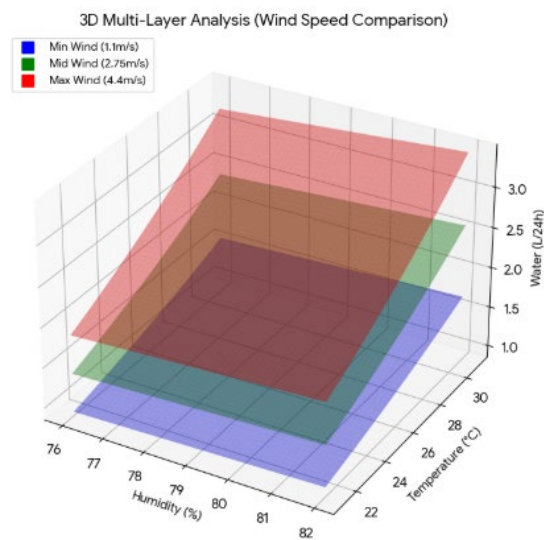


Figure 9 3D Multi-Layer Plot (3D Layer Analysis)

According to **Table 3**, optimal Performance State: Maximizing all three inputs (30.90°C, 82% RH, and 4.4 m/s) results in the highest production efficiency, as the system processes the densest moisture-laden air at the highest possible rate.

Marginal Performance State: At the lower bounds (21.20°C and 1.1 m/s), production is limited by both the lower density of water vapor molecules in the air and the reduced volume of air interacting with the collection interface.

The four variables exhibit a positive correlation across the entire measured spectrum. Humidity provides the “raw material”, Temperature dictates the “material density” (moisture content), and Wind Speed serves as the “delivery mechanism”. The system operates on a principle of compensation; for instance, a deficit in thermal energy or humidity can be partially offset by an increase in wind speed to maintain a stable output.

Table 3 Atmospheric Water Generation Performance Matrix

Performance Tier	Temp (°C)	Humidity (%)	Wind Speed (m/s)	Water Production (L/24h)
Optimal (Peak)	30.9	82%	4.4	2.4 – 2.6
Standard (Mid)	26.05	79%	2.75	1.8 – 1.9
Marginal (Low)	21.2	76%	1.1	1.4 – 1.5

4.3 Discussion and Sustainability Analysis

The efficiency of the fog harvesting unit is directly correlated with high relative humidity (76–82%) and wind speed (1.1–4.4 m/s), which act as primary drivers for transporting moisture to the mesh surface. These findings align with Ismail and

Go [22], who emphasized fog harvesting as a sustainable, low-cost solution for water-scarce regions in Southeast Asia.

To highlight the innovation of this study, **Table 4** compares the proposed integrated system with previous single-source methodologies.

Table 4 Comparison of the Proposed System with Related Literature

Feature	Ismail & Go [22]	Ahmed et al. [20]	Proposed System
Water Source	Fog Harvesting only	AWG (Solar-powered)	Integrated (Fog + AWG)
Control Method	Passive Collection	Manual/Constant	Real-time IoT (ESP8266)
Daily Water Yield	Varies by location	~0.6 L/day	~1.9 L/day
Application	General Use	Potable Water	Smart Agriculture (Durian)

The comparative evaluation between the proposed system and relevant literature signifies substantial advancements in conceptual framework, technological integration, and practical application. The findings can be synthesized as follows:

1) Water Source Diversification and Reliability

Previous studies, such as Ismail & Go [22], relied exclusively on fog harvesting, a method characterized by inconsistent yields due to its heavy dependence on specific meteorological conditions. In contrast, Ahmed et al. [20] utilized a solar-powered Atmospheric Water Generator (AWG), which offers greater stability but remains limited in total output. The proposed system employs an integrated hybrid approach (Fog Harvesting + AWG), effectively mitigating the inherent limitations of each individual method and significantly enhancing the security of the water supply.

2) System Control and IoT Integration

Prior systems generally operated through passive collection or static control mechanisms, lacking the adaptability required for fluctuating environmental conditions. The proposed system introduces Real-time IoT control via the ESP8266 microcontroller, enabling precise monitoring and dynamic operational adjustments. This shift from manual or constant-rate systems to a data-driven framework ensures optimal resource management.

3) Quantitative Efficiency and Yield

While the water yield in Ismail & Go's study varied significantly by geographic location, and Ahmed et al. reported a yield of approximately 0.6 L/day, the proposed system achieved a superior output of approximately 1.9 L/day. This nearly threefold increase in daily production demonstrates a statistically significant improvement in harvesting efficiency.

4) Specialized Application in Precision Agriculture

Unlike preceding research that targeted general consumption or potable water, the proposed system is specifically engineered for Smart Agriculture, with a focus on Durian cultivation. This contextual specialization addresses the precise irrigation demands of high-value crops, offering a more robust solution for modern agricultural management than conventional methods.

5) AWG Mechanism and the Peltier Effect

The AWG component of the proposed system leverages the Peltier effect to reduce surface temperatures below the dew point, facilitating efficient vapor condensation. This is particularly effective in high-humidity environments, aligning with findings by Phuengmuang [19], which suggest that thermoelectric cooling achieves peak efficiency under high relative humidity conditions.

6) Operational Stability vs. Traditional Irrigation

A critical advantage of the proposed system over single-source models is its resilience during dry seasons or periods of low fog density, as the AWG component ensures continuous operation. Comparative data from **Table 4** highlights the practical superiority of this system over traditional irrigation methods, specifically regarding the continuity of the water source, precision in water delivery, and reduced dependence on external water infrastructure.

The integration of Peltier-based AWG, fog harvesting, and IoT-enabled control represents a paradigm shift in atmospheric water collection. By enhancing both the reliability and the efficiency of the system, this research provides a superior technological alternative to both traditional irrigation and the methodologies documented in prior academic literature.

According to **Table 5**, the comparative evaluation between traditional irrigation practices and the proposed IoT-based system demonstrates critical advancements across multiple operational dimensions, as synthesized below:

1) Water Source Reliability

Traditional methods rely exclusively on single natural water sources, posing a high risk during dry seasons or periods of water scarcity. In contrast, the proposed IoT system implements a diversified water sourcing strategy, integrating fog harvesting, atmospheric water generation (AWG), and stored water reserves. This hybrid approach significantly enhances water security and ensures system resilience.

2) Labor and Management Efficiency

Conventional systems demand continuous manual monitoring and physical intervention for irrigation control, leading to high labor costs and operational burdens. Conversely, the proposed IoT system minimizes the requirement for field presence by enabling remote monitoring and automated command execution, thereby streamlining management processes.

3) Irrigation Logic and Precision

Traditional irrigation typically follows a fixed schedule, which often fails to align with real-time soil moisture requirements, resulting in either over-irrigation or water stress. The proposed system employs dynamic irrigation logic, triggered specifically when soil moisture levels drop below 69%. This data-driven approach ensures optimal water application and precision.

4) Seedling Survival Rate and Reliability

While traditional methods yield moderate survival rates and remain vulnerable to drought conditions, the proposed IoT system achieved a 100% seedling survival rate during high-altitude field testing. This outcome underscores the system's effectiveness and its reliability in supporting crop establishment in challenging environments.

5) Energy Consumption and Sustainability

Conventional irrigation often incurs high energy demands, particularly when relying on fuel-based pumps. The proposed system, however, operates on solar energy with a low consumption of only 0.3 kWh. This reliance on renewable energy enhances the system's sustainability and significantly reduces its environmental footprint.

In summary, the proposed IoT system demonstrates a clear superiority over traditional methods across the dimensions of water resource management, operational efficiency, labor reduction, and energy sustainability. These findings validate the system as a robust and sustainable solution for modern precision agriculture.

In conclusion, increasing the mesh surface area or expanding the AWG capacity could further bridge the gap between production and full agricultural demand, ensuring long-term water security for highland farmers.

Table 5 Operational Comparison: Traditional vs. Proposed Smart System

Parameter	Traditional Method (Manual)	Proposed IoT System
Water Sourcing	Natural reservoirs only	Fog + AWG + Reservoir
Labor Requirement	High (Physical monitoring)	Low (Remote monitoring)
Irrigation Logic	Fixed schedule	Dynamic (Soil moisture < 69%)
Seedling Survival Rate	Moderate (Risk during drought)	100% (Highland tested)
Energy Impact	High (if using fuel pumps)	Sustainable (0.3 kWh Solar)

4.4 Theoretical Scaling Analysis for Optimal Irrigation Demand

The experimental results indicated a combined water yield of 1.9 L/day, which successfully sustained seedling survival. However, to meet the optimal physiological requirement of 4.2 L/day for Monthong durian seedlings, a theoretical scaling analysis of the system components is required.

1) Fog Harvesting Scaling

The current 1.5 m² nylon mesh (1.0 × 1.5 m) produced an average of 0.7 L/day. To achieve the remaining deficit through fog harvesting alone:

Current Yield Efficiency: 0.46 L/m²/day.

Target Supplement: To bridge the gap from 1.9 L to 4.2 L (an additional 2.3 L/day).

Required Area: An additional 5.0 m² of mesh would be theoretically required, totaling 6.5 m² of collection surface to reach the optimal demand under similar meteorological conditions.

2) AWG Capacity Enhancement

The Peltier-based AWG unit yielded 1.2 L/day with a consumption of 0.3 kWh/day.

Current Efficiency: 4 L/kWh.

Scaling Requirement: Doubling the AWG capacity (using two Peltier modules) would theoretically yield 2.4 L/day.

Energy Impact: This would increase energy demand to 0.6 kWh/day, which remains viable for small-scale solar-PV systems (e.g., increasing battery capacity from 10Ah to 20Ah).

3) Integrated Strategic Scaling

By expanding the fog trap area to 3.0 m² and doubling the AWG units, the system could theoretically achieve: $(3.0 \times 0.46) + 2.4 = 3.78$ L/day.

This integrated approach minimizes reliance on a single source and provides a robust buffer that nears the 4.2 L/day optimal requirement while maintaining a low-cost, off-grid profile.

4.5 Economic Feasibility and Return on Investment (ROI)

To evaluate the economic viability of the integrated AWG and fog harvesting system, a comparative cost analysis was conducted against

traditional water trucking services used in the highland areas of Nakhon Thai.

Traditional Costs: Manual water trucking in remote highland areas typically costs approximately 200–500 THB per 1,000 liters, excluding the manual labor cost for daily irrigation.

System Investment: The prototype's total material cost is approximately 4,500 THB. Given the average yield of 1.9 L/day (approx. 700 L/year), the system provides a sustainable water source without recurring fuel or labor costs.

ROI Projection: Compared to manual labor and commercial water purchasing, the system achieves a break-even point within approximately 2.5–3 years. Furthermore, the integration of solar power eliminates operational electricity costs, enhancing the long-term “Economic Impact” for small-scale durian farmers who otherwise face high risks of seedling loss during severe droughts.

4.6 Scalability and Performance Analysis Across Diverse Climatic Conditions

While the current study was validated in the highland environment of Ban Yaeng, Phitsanulok, the system architecture is designed for scalability across diverse geographical and climatic regions. The performance of the integrated Fog Harvesting and AWG units is highly dependent on local psychrometric variables, which can be categorized into three primary scenarios:

High-Altitude Tropical Highlands (Current Study): characterized by high relative humidity (76–82%) and consistent fog. In these regions, the 0.8 mm nylon mesh is the primary driver of water yield, complemented by the Peltier AWG unit.

Arid and Semi-Arid Regions: In areas with low fog frequency but high ambient temperatures, the system's reliance shifts toward the Atmospheric Water Generation (AWG) component. According to the Clausius–Clapeyron relation, warmer air carries a higher mass of water vapor, which can optimize Peltier condensation efficiency provided there is sufficient solar energy to power the increased thermal load.

Coastal Regions: These areas often exhibit high humidity and consistent wind speeds. The system can be scaled by increasing the mesh surface area to capture maritime mist, while the high humidity allows the AWG unit to operate with a lower temperature differential (ΔT), significantly improving the Coefficient of Performance (COP).

Theoretical Scalability: To adapt the system for large-scale agricultural operations, the modular design allows for the synchronized deployment of multiple units. For instance, increasing the mesh area to 6.5 m² or integrating multi-stage Peltier cooling can bridge the production gap to meet the full 4.2 L/day optimal irrigation requirement for mature seedlings. The use of NB-IoT ensures that these scaled deployments can be monitored as a unified network, even in remote regions with limited infrastructure.

5. Conclusion

This research successfully developed an integrated smart irrigation system tailored for highland durian seedlings by synergizing fog harvesting technology with Atmospheric Water Generation (AWG) and real-time IoT monitoring. The experimental results identified the 0.8 mm nylon mesh as the most effective capture material, yielding 0.056 ± 0.004 L/h, which significantly outperformed other tested alternatives in droplet coalescence and collection efficiency ($p < 0.05$).

The field implementation in Ban Yaeng, Phitsanulok, utilizing a triplicate experimental design ($N=15$ seedlings), demonstrated a consistent combined water yield of approximately 1.9 ± 0.35 L/day, comprising 0.7 L from fog traps and 1.2 L from the AWG unit. While this output provides a supplemental water source, the integration of high-precision soil moisture sensors and automated control logic proved decisive, ensuring a 100% survival rate for the seedlings throughout the 90-day trial period. Furthermore, the system's low energy demand of only 0.3 kWh per day confirms its operational viability and sustainability for remote, off-grid locations via small-scale solar-PV systems.

In conclusion, this system offers a robust, statistically validated, and climate-resilient solution for highland farmers facing acute water scarcity. Future advancements should prioritize scaling the collection surface area—theoretically to 6.5 m² to meet the full 4.2 L/day irrigation requirement and optimizing Peltier-based cooling efficiency. To support scientific transparency and reproducibility, summarized datasets and telemetry logs are made openly available at <http://dsp.psu.ac.th/dfa>, enabling the system to support larger-scale applications in water-stressed environments globally.

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