

An internet of things-based solar dryer: A conceptual design for seaweed cultivation in Madura

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Abstract. This research proposes a conceptual design for an Internet of Things (IoT)-enhanced solar dryer tailored specifically for seaweed cultivation on Madura Island, Indonesia. The study addresses the critical bottleneck in the traditional sun drying process, which is highly susceptible to weather variations, contamination, and inconsistent drying quality. Utilizing Fahmideh and Zowghi's IoT Development Framework, the research encompasses both the analysis and design phases. The analysis phase identifies the environmental conditions, operational requirements, and technical specifications necessary for optimal seaweed drying on Madura Island. Based on these insights, the design phase develops a comprehensive system architecture incorporating advanced IoT components such as sensors, actuators, connectivity solutions, and data management platforms. The proposed IoT-enhanced solar dryer aims to create a controlled and optimized drying environment, significantly improving drying efficiency and ensuring consistent product quality. By enabling farmers to meet increasing demand and achieve higher market prices for their produce, this innovative solution enhances the economic viability of seaweed farming on Madura Island. Ultimately, this research contributes to the sustainability and growth of Indonesia's blue economy by promoting advanced agricultural practices and increasing the competitiveness of the seaweed industry.

1 Introduction

Indonesia, with its extensive coastline stretching over 54,716 kilometres, stands at the forefront of the blue economy, leveraging its abundant marine resources to drive economic growth and sustainability. The blue economy, which includes the sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of ocean ecosystems, is particularly vital for Indonesia [1]. Given its geographical advantage, Indonesia has made significant strides in various marine sectors, including fisheries, and notably, seaweed cultivation [2].

Seaweed cultivation has emerged as a significant sector within Indonesia's blue economy. The country is one of the world's largest producers with over 5 million tons of seaweed [3]. The cultivation is taking place in coastal regions such as Bali, Sulawesi, and East Nusa Tenggara. Among these regions, Madura Island is a key player. Known for its extensive seaweed farming, Madura Island contributes significantly to local economies, providing livelihoods for many coastal communities. The harvested seaweed from Madura is utilized in various industries, including food, cosmetics, pharmaceuticals, and biofuels, highlighting its economic importance.

However, the seaweed cultivation process on Madura Island faces a critical bottleneck in the drying

stage [4]. Traditionally, farmers rely on sun drying, where seaweed is spread out on tarpaulins or drying racks under the sun. While this method is cost-effective and utilizes natural sunlight, it has several significant drawbacks [5], [6], [7]:

- **Weather Variations:** Sun drying is highly dependent on weather conditions. Rain, high humidity, and cloudy days can severely disrupt the drying process, leading to delays and potential spoilage of the seaweed.
- **Contamination:** Exposure to open air during sun drying makes the seaweed vulnerable to contamination from dust, dirt, insects, and other pollutants. This contamination can degrade the quality of the seaweed, making it less desirable for commercial use.
- **Inconsistent Drying Quality:** Sun drying can result in uneven drying due to variations in sunlight exposure and airflow. This inconsistency affects the overall quality and market value of the dried seaweed.

The reliance on traditional sun drying methods severely hampers the ability of Madura's seaweed farmers to meet the increasing demand for high-quality seaweed. This bottleneck not only limits production capacity but also impacts the farmers' income, as they are unable to ensure consistent supply and quality required by buyers. The fluctuating and often insufficient drying conditions lead to significant

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economic losses, pushing many farmers into precarious financial situations.

The traditional sun drying methods used by seaweed farmers on Madura Island are proving to be a significant barrier to meeting the growing demand for high-quality seaweed. This bottleneck not only restricts production capacity but also adversely affects the farmers' income due to the inability to ensure the consistent supply and quality required by buyers. The unpredictable and often inadequate drying conditions result in substantial economic losses, leaving many farmers in precarious financial situations.

To overcome the limitations imposed by traditional sun drying methods, it is essential to explore innovative solutions that can enhance the efficiency and reliability of the seaweed drying process. The current practices are not only insufficient to meet the growing market demand but also expose farmers to significant economic risks due to inconsistent product quality and supply. This scenario underscores the urgent need for a more advanced drying system that can mitigate these challenges and support the sustainable growth of the seaweed industry on Madura Island.

Drawing from the challenges above, the objective of study, therefore, is to propose a conceptual design for an Internet of Things (IoT)-enhanced solar dryer tailored specifically for seaweed cultivation on Madura Island, Indonesia. This study particularly aims to address the critical bottleneck in the traditional sun drying process, which is currently hampering the ability of local seaweed farmers to meet the increasing demand for high-quality seaweed. By integrating modern IoT technologies into the drying process, this research seeks to create a more efficient, reliable, and consistent method for drying seaweed. This result of this study is expected to fill a critical gap in the literature by addressing the lack of comprehensive studies on IoT applications for seaweed drying in Indonesia. By developing a conceptual design specifically tailored to the conditions on Madura Island, this study provides a blueprint for integrating advanced technologies into traditional agricultural practices.

In practical sense, the envisioned system will leverage sensors, actuators, and connectivity solutions to optimize drying conditions, reduce contamination risks, and improve product quality. Ultimately, this study aspires to enhance the productivity and income of seaweed farmers on Madura Island, contributing to the sustainability and growth of Indonesia's blue economy. This contribution is particularly significant for regions with similar climatic and economic conditions, offering a scalable and adaptable solution to common drying challenges.

2 Related works

Current literature and implementations of seaweed drying systems in Indonesia predominantly focus on traditional methods and basic mechanized systems [7], [8], [9], [10]. Traditional sun drying, which involves spreading seaweed on tarpaulins or racks under the sun,

is widely documented due to its low cost and simplicity. However, this method is fraught with challenges such as dependence on weather conditions, risk of contamination, and inconsistent drying quality. Mechanized drying systems, though more advanced than sun drying, are still relatively basic and often lack the technological sophistication needed to optimize the drying process [8]. Studies highlight these challenges, noting that mechanized systems, while reducing drying time compared to sun drying, still suffer from issues like uneven drying and energy inefficiency [9].

Existing research highlights the critical bottlenecks in conventional drying methods but lacks comprehensive attention to integrating Internet of Things (IoT) solutions. For instance, studies on seaweed drying in Indonesia often focus on improving traditional methods or developing low-cost mechanized solutions without leveraging advanced technologies like IoT [11][4]. These approaches fail to address the potential for real-time monitoring and control that IoT can provide, which is crucial for achieving consistent and high-quality drying outcomes.

Globally, there have been significant advancements in IoT applications for agriculture and drying processes [12], [13]. Moreover, IoT has been successfully implemented in precision agriculture to monitor soil moisture [14], temperature, and crop health [15], leading to improved crop yields and resource efficiency. Similarly, IoT-based drying systems for crops like grains and fruits have shown substantial improvements in drying efficiency and product quality by enabling real-time monitoring and control of drying conditions [15], [16]. These systems use sensors to collect data on temperature, humidity, and moisture content, which are then processed by algorithms to optimize the drying process. However, specific adaptations of these technologies for Indonesian seaweed drying remain unexplored in the literature.

This gap in the research indicates a significant opportunity to innovate and tailor IoT-based solutions to the unique needs of Indonesia's seaweed industry. Given the unique climatic and environmental conditions in Indonesia, especially in Madura, there is a pressing need for a customized approach that addresses the specific challenges faced by local seaweed farmers. The integration of IoT into seaweed drying systems can provide several benefits, including precise control over drying parameters, reduced contamination risks, and improved consistency and quality of the dried seaweed. Moreover, by leveraging IoT technology, it is possible to develop scalable and cost-effective solutions that can be adopted by small and large-scale seaweed farmers alike.

Drawing from the review above, while the existing literature provides a foundation for understanding the challenges of traditional and basic mechanized seaweed drying methods in Indonesia, it falls short of exploring the potential of IoT-enhanced solutions for seaweed drying especially in the Madura context. This study, therefore, aims to fill this gap by developing a conceptual design for an IoT-based solar dryer tailored to the needs of Madura Island's seaweed industry,

thereby enhancing productivity, quality, and sustainability.

3 Research Method

In the realm of IoT development, there is no universally applicable framework that fits all use cases and scenarios. Each IoT implementation must be tailored to the specific requirements and constraints of the application domain, making it essential to adopt a flexible and adaptable approach. To guide the development of the IoT-enhanced solar dryer for seaweed cultivation on Madura Island, this study adopts the framework proposed by Fahmideh and Zowhi [17].

This IoT Development Framework is derived from existing design frameworks and is specifically designed to accommodate the diverse and dynamic nature of IoT projects. This framework was chosen for several key reasons. First, it offers a comprehensive and structured methodology for developing IoT systems, encompassing all critical phases from initial analysis to final implementation and testing. This ensures a systematic approach to identifying and addressing the unique challenges of seaweed drying on Madura Island.

Second, Fahmideh and Zowghi's framework emphasizes flexibility and adaptability, which are crucial for tailoring the IoT solution to the specific environmental, operational, and technical conditions of the region. The framework's ability to accommodate diverse requirements makes it well-suited for the dynamic and variable conditions encountered in seaweed farming.

Third, the framework facilitates the integration of advanced IoT components such as sensors, actuators, connectivity solutions, and data management platforms. This is essential for creating a robust and efficient system that can monitor and control the drying process in real-time, thereby improving drying efficiency, consistency, and quality.

This framework suggests four stages of IoT development including analysis phase; design phase; implementation and test phase; and deployment phase as seen in Figure 1. However, since this study aims to provide a conceptual design of the IoT-enhanced solar dryer, only the analysis and design phases are applicable.

- **Analysis Phase:** In this phase, the specific requirements of the seaweed drying process are identified. This involves understanding the domain specific factors such as environmental conditions, drying parameters, and challenges faced by seaweed farmers on Madura Island. Key factors such as temperature, humidity, drying time, and potential contaminants are examined to establish the necessary specifications for the IoT system. This phase also includes a review of existing technologies and practices in seaweed drying, as well as an assessment of the potential benefits and limitations of integrating IoT solution.
- **Design Phase:** Based on the insights gained from the analysis phase, the design phase involves developing

the conceptual architecture of the IoT-enhanced solar dryer. This includes selecting appropriate sensors, actuators, and connectivity solutions that will form the core components of the system. The design phase also encompasses the creation of a system architecture diagram, outlining how the various components will interact and communicate. Additionally, this phase considers the software requirements for data collection, processing, and user interface design, ensuring that the system is both functional and user-friendly.

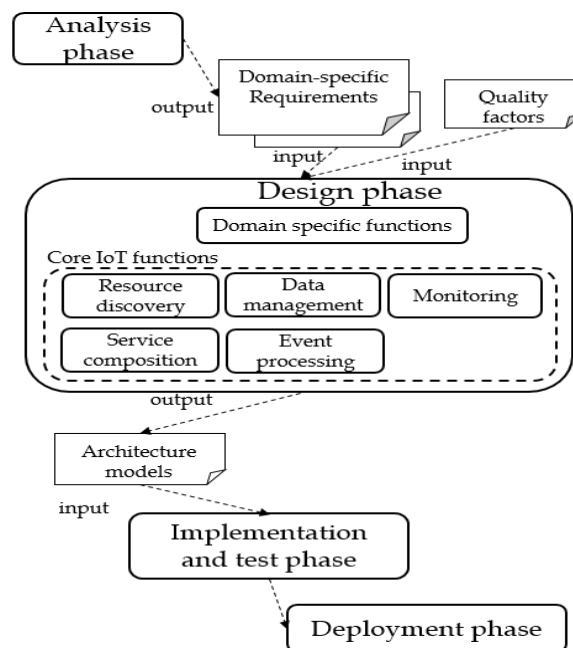


Fig. 1. IoT Development Framework based on [17, p.10].

4 Results and discussion

This results section discusses the key findings how the IoT-enhanced solar dryer was designed to address the challenges and meets the specific needs of seaweed farmers on Madura Island. Building from the IoT development framework, the discussion begins by presenting the findings from the analysis phase and then moves on to the design phase.

4.1 Analysis phase

The analysis phase focused on understanding the domain specific function of the IoT-enhanced solar dryer for seaweed cultivation on Madura Island. This involved an analysis of the environmental conditions that is characterized by distinct wet and dry seasons, with high humidity and frequent rainfall during the rainy season. These conditions pose significant challenges for traditional sun drying methods, which rely on consistent sunlight and low humidity for effective drying.

The analysis also identified that maintaining precise temperature and humidity levels is crucial for the optimal drying of seaweed. Variations in these parameters can lead to uneven drying, spoilage, and

reduced nutritional and commercial value of the seaweed. Another important challenge identified in this phase is contamination risks and limitations of traditional and mechanized drying methods that expose seaweed to potential contaminants such as dust, insects, and pollutants. This in particular highlights the need for an innovative solution of the traditional drying methods using an enhanced IoT.

Drawing from the above environmental and operational analysis, the study identified the materials and resources required for developing the IoT-enhanced solar dryer for seaweed as follows:

a. Microcontroller (ESP32)

The ESP32 microcontroller is a low-cost, low-power system on a chip (SoC) series that has become widely popular in IoT projects due to its rich features and robustness. It incorporates a dual-core processor clocked at up to 240 MHz, providing ample computational capabilities for complex tasks. The ESP32 is particularly noted for its integrated Wi-Fi and dual-mode Bluetooth capabilities, which make it ideal for projects requiring wireless communication. In the context of an IoT-enabled solar dryer system, the ESP32 offers several advantages [18]. It has built-in temperature, touch, and humidity sensors allow for direct environmental monitoring without requiring additional external sensors, reducing system complexity and cost[19]. Moreover, the ESP32's ability to support multiple sleep modes ensures energy efficiency, which is crucial for systems reliant on limited power sources, such as solar energy [20]. Figure 2 shows picture of Microcontroller ESP32.



Fig. 2. Microcontroller ESP32 [21].

b. Temperature and Humidity Sensor (DHT)

The DHT sensor series, specifically popular models like the DHT11 and DHT22, are widely utilized in various IoT applications due to their cost-effectiveness and ease of use. These sensors are compact digital devices designed to simultaneously measure ambient temperature and humidity. The DHT sensors are known for their reliability and provide a digital output signal that can be easily interfaced with a range of microcontrollers, including the ESP32.

The DHT11 model provides a temperature measurement range of 0 to 50 degrees Celsius with a ± 2 degrees Celsius accuracy and a humidity measurement

range of 20% to 80% with 5% accuracy. The DHT22, on the other hand, offers an enhanced temperature range of -40 to 80 degrees Celsius with a ± 0.5 degrees Celsius accuracy and a humidity range of 0% to 100% with 2-5% accuracy [22]. In the context of a solar dryer system, the DHT sensors' ability to operate in varied environmental conditions makes them particularly useful. They continuously monitor the microclimate within the dryer, providing crucial data that the system's microcontroller uses to adjust parameters such as fan speed and vent positions, thereby optimizing the drying process and ensuring product quality [23].

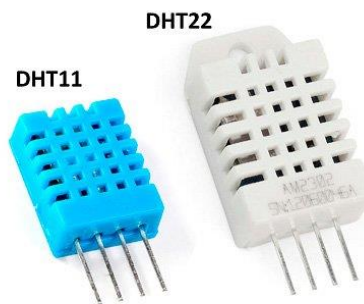


Fig. 3. DHT11 and DHT12 sensors [24].

Furthermore, the DHT sensors' low power consumption and minimal maintenance requirements make them well-suited for sustainable and autonomous systems powered by renewable energy sources, such as solar panels. Their digital signal output facilitates straightforward integration into IoT applications, where remote data monitoring and analysis can be implemented via cloud computing solutions [25]. Figure 3 shows the DHT sensors.

c. Fan control system

The fan control system comprises a digital anemometer, ESP32 microcontroller, exhaust fan, relay module, and a power system consisting of solar panels and batteries. The digital anemometer continuously measures the wind speed inside the solar dryer. Simultaneously, additional sensors monitor temperature and humidity levels. This environmental data is sent to the ESP32 microcontroller for processing.

The ESP32 microcontroller is the central processing unit, receiving real-time data from the digital anemometer and other sensors. It employs an adaptive control algorithm to analyze the collected data and make decisions regarding the operation of the exhaust fan. For instance, if the humidity inside the dryer rises due to moisture released from the seaweed, the microcontroller detects this change [26]. It determines that increasing the fan speed will help to expel the moist air more effectively, promoting faster drying. Once the microcontroller has processed the data and decided on the optimal fan speed, it sends control signals to the relay module. The relay module interfaces between the microcontroller and the exhaust fan, adjusting the power supplied to the fan. By varying the fan speed, the system can modulate the airflow within the dryer, ensuring that

the internal conditions remain conducive to efficient drying.

d. Solar panels and battery system

Integrating solar panels and battery systems is essential for powering IoT applications in remote or off-grid locations, such as solar dryers. Solar panels, which convert sunlight into electricity, are chosen for their efficiency and durability, which are crucial for withstanding varied environmental conditions and ensuring consistent energy conversion [27]. The energy produced is stored in batteries, typically lithium-ion, due to their high energy density and low self-discharge rates, allowing for continuous operation through fluctuating solar availability [28].

This combination guarantees an uninterrupted power supply and enhances the system's sustainability by reducing operational costs and dependency on non-renewable energy sources. Advanced battery management systems further optimize performance, extending the lifespan and safety of the storage system, which is crucial for maintaining the reliability of IoT devices in agricultural settings.

4.2 Design phase

The subsequent phase is design that leveraged the insights generated from the analysis phase to create a robust conceptual architecture for the IoT-enhanced solar dryer. This phase focused on integrating the identified materials and resources, such as specific sensors, actuators, connectivity solutions, and data management platforms, into a cohesive system. The goal was to develop a design that optimizes drying efficiency, ensures consistent product quality, and addresses the unique challenges faced by local seaweed farmers.

The proposed design of the IoT-enabled solar dryer system focuses on optimizing the drying process of seaweed by leveraging real-time environmental data and adaptive control mechanisms. This system utilizes advanced IoT technologies to monitor and control the internal conditions of the solar dryer. Figure 4 illustrates the proposed design of this system, with the overall design workflow and operational functions as follows:

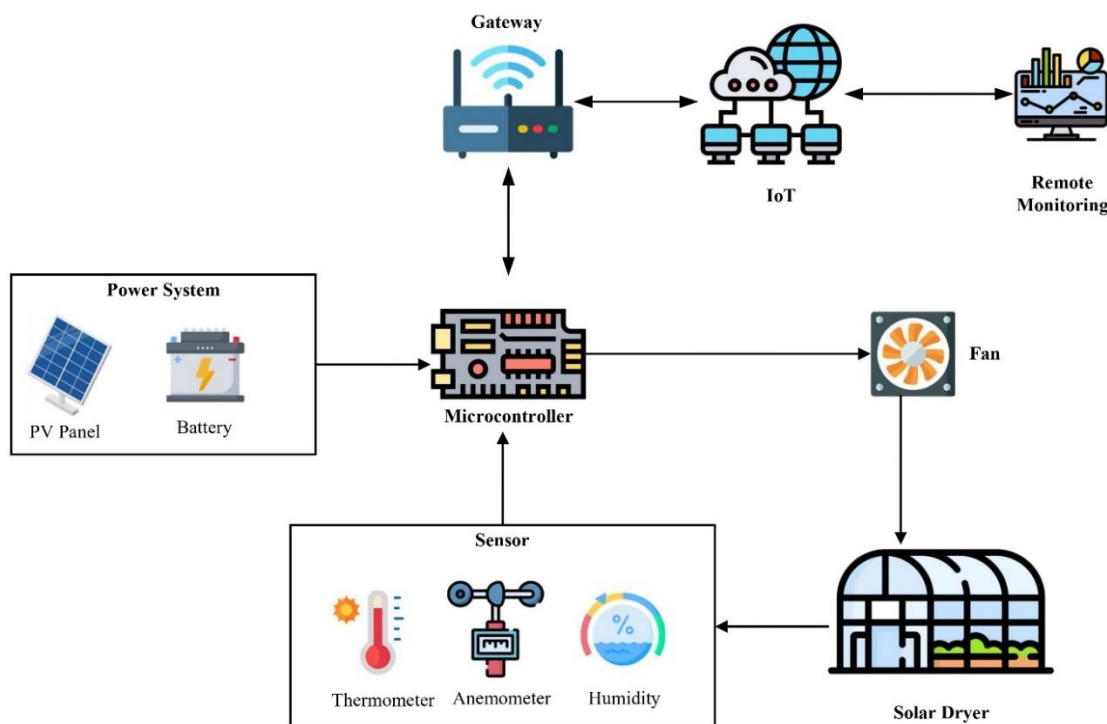


Fig. 4. Proposed design IoT based solar dryer for seaweed.

• Data Collection

System begins with the continuous collection of environmental data. Sensors, including the digital anemometer for wind speed and DHT sensors for temperature and humidity, gather real-time information about the conditions inside the solar dryer. This data is crucial for monitoring and adjusting the drying process.

• Data Transmission

The collected sensor data is transmitted to the ESP32 microcontroller, which serves as the system's central

processing unit. The microcontroller receives the data in real-time, enabling immediate analysis and response.

• Data processing and analysis

ESP32 microcontroller processes the incoming data using an adaptive control algorithm. This algorithm analyzes variations in temperature, humidity, and wind speed to determine the necessary adjustments needed to maintain optimal drying conditions. For instance, if the humidity inside the dryer increases due to moisture

release from the seaweed, the algorithm will calculate the optimal fan speed to expel the moist air effectively.

• **Controls action**

Based on the processed data, the microcontroller sends control signals to the relay module connected to the exhaust fan. The relay module adjusts the power supply to the fan, regulating its speed. This dynamic control of the fan ensures that the airflow within the dryer is optimized for efficient moisture removal and temperature stabilization.

• **Power Management**

The system is powered by solar panels, which convert sunlight into electricity stored in lithium-ion batteries. This renewable energy source ensures that the dryer operates sustainably and continuously, even during periods of low sunlight. The power management system includes advanced battery management to optimize energy usage and extend battery life.

• **Remote monitoring and control**

ESP32 microcontroller is connected to an IoT gateway, which transmits data to a cloud platform. This setup allows for remote monitoring and control of the drying process. Users can access real-time data, analyze historical data trends, and make necessary adjustments to the system from any location with internet access. This remote capability enhances the operational flexibility and efficiency of the solar dryer.

• **Continuous optimization**

The system is designed to continuously adapt to changing environmental conditions. By maintaining a real-time feedback loop, the microcontroller can make ongoing adjustments to the fan speed and other parameters, ensuring that the drying conditions remain optimal. This continuous optimization leads to improved drying efficiency, better product quality, and reduced energy consumption.

5 Conclusion

This study presents a conceptual design for an IoT-enhanced solar dryer tailored to the specific needs of seaweed cultivation on Madura Island, Indonesia. The research addresses the critical challenges faced by local seaweed farmers who rely on traditional sun drying methods, which are susceptible to weather variations, contamination, and inconsistent drying quality. By integrating IoT technology, the proposed solar dryer offers a promising solution to these issues, providing real-time monitoring and control over the drying process to ensure improved efficiency, reliability, and quality.

Future work should focus on developing and testing prototypes of the proposed IoT-enhanced solar dryer to validate its effectiveness in real-world conditions. Additionally, further research is needed to explore the scalability of this technology for broader adoption across other seaweed farming regions in Indonesia. By addressing these next steps, this study aims to pave the way for a more efficient, sustainable, and economically viable seaweed industry in Indonesia, ultimately strengthening the country's position in the global seaweed market

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