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Design and Development of PADDY-SMART as a Solar-Powered Integrated Paddy Cleaning and Drying System with IoT-Based Monitoring for Sustainable Agriculture

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ABSTRACT

Post-harvest rice processing, especially the process of cleaning and drying grain, requires a lot of energy and still uses a lot of conventional energy sources and power grids. The usual drying method depends on the weather and can cause an uneven decrease in moisture content. Meanwhile, continuous monitoring can reduce the efficiency and accuracy of the process. This research discusses the design and manufacture of PADDY-SMART, which is a system that combines the process of cleaning and drying grain based on solar energy, and is equipped with a monitoring system that utilizes the Internet of Things to support environmentally friendly agriculture. The system is made with the aim of using solar energy as the main energy while combining the cleaning and drying processes in one system so that the post-harvest processing process is more efficient and reduces dependence on conventional energy sources. The development stages include the design of the system, production and management of energy from solar panels, the installation and operation of machines for cleaning and drying rice, and the creation of an Internet of Things based monitoring system to monitor operating conditions directly and continuously. The system is designed to monitor parameters such as drying temperature, relative humidity, and solar panel condition through a digital monitoring screen. Performance evaluation is carried out by analyzing solar energy usage, drying temperature stability, reduced moisture content in rice, cleaning effectiveness, and overall system performance. PADDY-SMART offers an integrated way to use renewable energy for the post-harvest process of rice with the help of direct and continuous monitoring. This system is able to improve the consistency of the drying process, reduce the use of energy from conventional sources, and support the application of smart and environmentally friendly agricultural technology. Thus, PADDY-SMART shows the potential by combining solar energy and Internet of Things technology to create a more efficient and environmentally friendly rice processing system.

1. Introduction

Rice is one of Indonesia's most important agricultural commodities, playing a fundamental role in ensuring national food security and meeting the dietary needs of its population. Following harvesting, paddy undergoes several post-harvest processing stages to preserve grain quality and ensure its suitability for storage and subsequent processing. These stages typically involve removing

foreign materials and impurities, followed by drying to achieve an appropriate moisture content for safe storage [1]. Proper post-harvest management is essential for minimizing quantitative and qualitative losses, preventing grain deterioration, and maintaining the overall quality of harvested paddy. Nevertheless, conventional cleaning and drying operations continue to face several challenges, particularly those associated with energy consumption, dependence on environmental conditions, and reliance on manual process monitoring [2].

Drying is a critical post-harvest operation because excessive moisture content promotes microbial growth, accelerates grain deterioration, and reduces storage stability and shelf life [3]. Traditional sun drying remains widely practiced due to its simplicity and relatively low operating costs. However, its effectiveness is strongly influenced by prevailing weather conditions [4]. Variations in solar radiation intensity, ambient temperature, relative humidity, and rainfall can prolong drying times and produce nonuniform moisture distributions within the grain. Such inconsistencies may adversely affect grain quality and increase the risk of post-harvest losses. Although mechanical drying systems provide greater control over operating conditions and improve drying consistency, their dependence on electricity or conventional fuels can result in substantial energy consumption and higher operating costs [5]. Consequently, there is a growing need for alternative drying technologies that combine reliable performance with improved energy efficiency and environmental sustainability.

The integration of solar photovoltaic (PV) technology into agricultural processing systems offers a promising approach to reducing dependence on conventional energy sources during post-harvest operations. PV technology converts incident solar radiation directly into electrical energy, which can subsequently power the equipment required for paddy cleaning and drying. Given the relatively high availability of solar radiation in tropical regions such as Indonesia, photovoltaic systems offer considerable potential for supporting decentralized and energy-efficient agricultural processing. Furthermore, the utilization of renewable solar energy can contribute to reducing fossil fuel consumption, lowering operational costs, and minimizing the environmental impacts associated with conventional post-harvest technologies. Integrating PV systems with paddy processing equipment therefore represents a potentially effective strategy for developing more sustainable and energy-efficient agricultural operations [6].

In addition to energy efficiency, effective monitoring of drying conditions is essential for ensuring consistent process performance and maintaining grain quality. Conventional monitoring methods typically require operators to measure and assess parameters such as temperature, relative humidity, and equipment operating conditions manually. These approaches can be labor-intensive, time-consuming, and susceptible to measurement inconsistencies or delayed corrective actions. Recent developments in Internet of Things (IoT) technology provide opportunities to overcome these limitations through the integration of sensors, communication networks, and digital monitoring platforms [7]. IoT-enabled systems facilitate continuous data acquisition and real-time transmission of operating parameters, allowing users to observe drying conditions remotely and identify variations that may affect process performance. Parameters such as drying temperature, relative humidity, and photovoltaic energy system conditions can be monitored through an integrated digital interface, thereby improving operational visibility and supporting more informed process management [8].

Previous studies have investigated the application of solar energy in agricultural drying systems and the incorporation of IoT technologies for monitoring environmental and operational parameters. These developments demonstrate the potential of renewable energy and digital monitoring technologies to improve the efficiency and reliability of post-harvest operations. However, existing approaches often emphasize individual functions, particularly solar-assisted drying or IoT-based monitoring, rather than the integration of multiple post-harvest processes within a unified system.

Specifically, the combined implementation of paddy cleaning, drying, photovoltaic energy utilization, and IoT-enabled monitoring within a single operational platform remains an area requiring further investigation. Integrating these functions could reduce operational complexity, improve coordination between processing stages, and provide continuous information on system performance [9].

Accordingly, a research opportunity exists to develop an integrated post-harvest processing system that simultaneously addresses energy efficiency, grain cleaning and drying performance, and real-time operational monitoring. Such a system should utilize renewable solar energy while incorporating appropriate mechanical processing components and sensor-based monitoring technologies. The integration of these elements is expected to support more efficient energy utilization, improve the consistency of drying conditions, and reduce the need for continuous on-site supervision. Furthermore, an integrated approach could facilitate the adoption of smart agricultural technologies, particularly in rural and decentralized agricultural settings where access to conventional energy infrastructure may be limited [10].

To address these requirements, the present study proposes the development of PADDY-SMART, an integrated solar-powered paddy cleaning and drying system equipped with an IoT-based monitoring platform. The proposed system combines photovoltaic panels as a renewable electrical power source, mechanical units for paddy cleaning and drying, and an IoT-based monitoring architecture within a unified post-harvest processing framework [11]. The monitoring subsystem is designed to acquire and transmit operational data, including drying temperature, relative humidity, and photovoltaic energy system conditions, enabling continuous observation of system performance. The proposed system is evaluated in terms of photovoltaic energy utilization, drying temperature stability, moisture content reduction, cleaning effectiveness, and overall operational performance. Through the development and assessment of PADDY-SMART, this study seeks to contribute to the advancement of integrated, energy-efficient, environmentally sustainable, and digitally enabled post-harvest processing technologies for rice production [12].

2. Methodology

2.1. Research Flow and Control Strategy Framework

The research methodology adopted in this study follows a systematic approach encompassing problem identification, literature review, system design, engineering calculations, system integration, and evaluation of the proposed PADDY-SMART system. The methodological framework is structured to ensure that the developed system addresses the operational requirements of paddy cleaning and drying while incorporating renewable energy utilization and IoT-based monitoring capabilities.

The initial stage involves conducting a case study to identify existing challenges and operational requirements associated with conventional paddy post-harvest processing. Particular attention is given to limitations related to cleaning efficiency, drying performance, energy consumption, and the monitoring of operating conditions. The findings from this preliminary investigation provide the basis for defining the functional requirements and design specifications of the proposed system.

Subsequently, a comprehensive literature review is undertaken to examine relevant technologies, design principles, and engineering approaches associated with solar-powered agricultural equipment, mechanical grain cleaning and drying systems, and IoT-enabled monitoring applications. The literature review supports the selection of suitable components, system configurations, and integration strategies, ensuring that the proposed design is informed by established engineering practices and relevant technological developments.

Based on the outcomes of the preliminary investigation and literature review, the system design stage is organized into four principal components: three-dimensional (3D) mechanical design, photovoltaic power system design, paddy cleaning and drying unit design, and IoT-based monitoring system development. The 3D mechanical design establishes the physical configuration, dimensions, structural arrangement, and positioning of the system components to ensure functional compatibility and efficient utilization of available space. The photovoltaic subsystem is designed to provide the electrical energy required to operate the cleaning, drying, and monitoring equipment, considering the anticipated power demand and operating requirements.

The paddy cleaning and drying unit is designed to integrate the removal of impurities and moisture reduction into a coordinated post-harvest processing sequence. This configuration aims to improve operational efficiency by combining two essential processing stages within a single system. Meanwhile, the IoT subsystem incorporates appropriate sensors and communication components to facilitate the acquisition, transmission, and visualization of relevant operating parameters. The monitoring architecture is intended to provide continuous information on drying temperature, relative humidity, and photovoltaic system conditions, thereby supporting real-time observation of the processing environment.

Following the completion of the individual subsystem designs, the components are integrated into a unified PADDY-SMART configuration. Engineering calculations are then performed to assess the preliminary feasibility and suitability of the proposed design. These calculations provide a quantitative basis for evaluating key design parameters, including mechanical requirements, electrical power demand, and the compatibility of the photovoltaic system with the anticipated operating loads. The results are used to assess the proposed configuration and identify any necessary design refinements before implementation.

The subsequent stage involves compiling and analyzing the design outcomes to establish the overall configuration and expected operational characteristics of the integrated PADDY-SMART system. The analysis focuses on the interaction between the mechanical processing components, photovoltaic power supply, and IoT-based monitoring subsystem. Finally, the research concludes by summarizing the principal design outcomes, assessing the extent to which the research objectives have been achieved, and identifying potential opportunities for further development and performance improvement.

The overall research procedure is illustrated in Figure 1, which presents the sequential relationship between problem identification, literature review, system design, engineering calculations, system integration, results analysis, and conclusion.

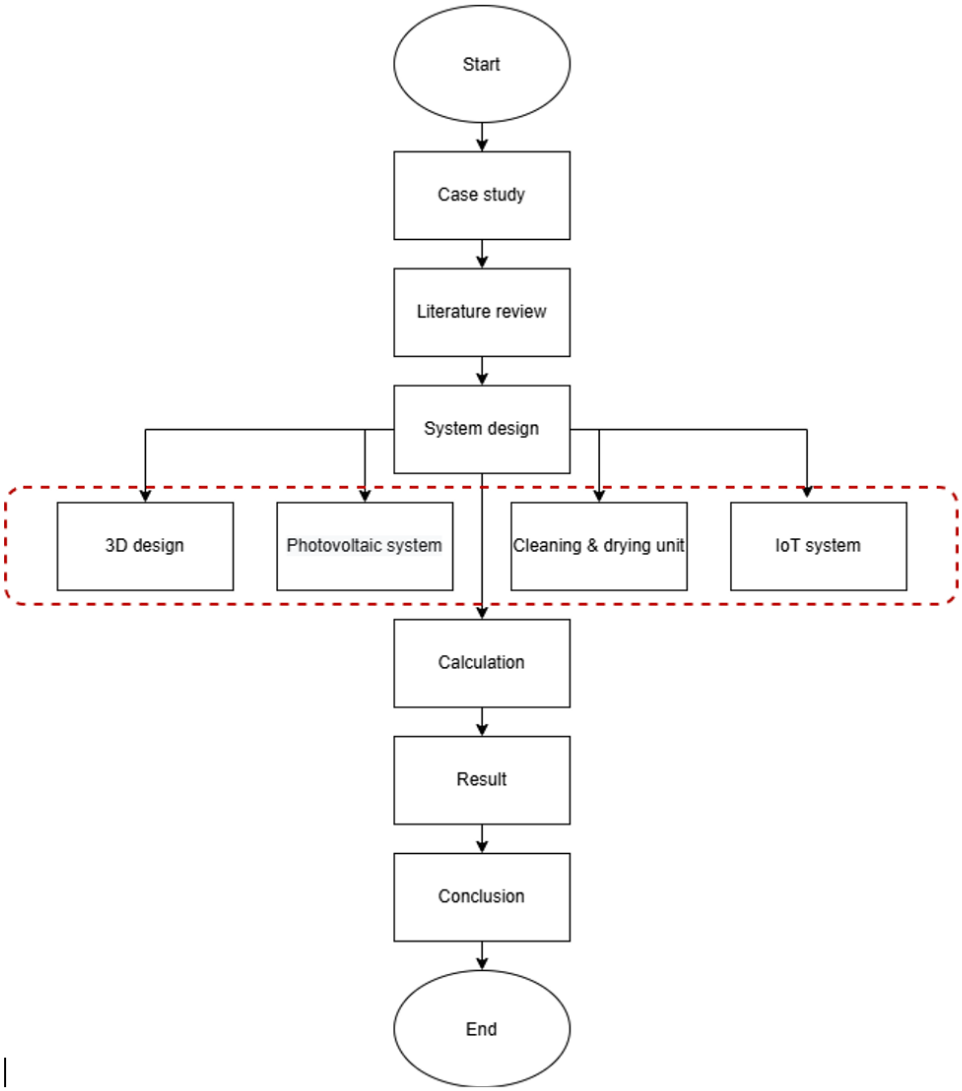


Fig. 1. Research methodology flowchart for System Design Framework of PADDY-SMART

2.2 Power and Energy Requirements

The power and energy requirements of the PADDY-SMART system are determined by evaluating the electrical loads associated with the paddy cleaning unit, drying unit, and Internet of Things (IoT)-based monitoring subsystem. An assessment of these requirements is essential for ensuring that the photovoltaic (PV) power generation and energy storage systems are appropriately sized to support reliable and continuous operation. The analysis involves calculating the total electrical power demand, estimating energy consumption over the specified operating period, and determining the required capacities of the photovoltaic modules and battery storage system.

The total electrical power demand is calculated by summing the rated power consumption of the individual components, as expressed in Equation (1) [13].

$$P_{total} = P_{cleaning} + P_{drying} + P_{IoT} \quad (1)$$

The total energy requirement is subsequently estimated based on the electrical power demand and the duration of system operation. Energy consumption is calculated as the product of electrical

power and operating time, providing a fundamental basis for determining the capacity of the photovoltaic power generation and energy storage systems. Assuming that all electrical components operate simultaneously at constant power throughout the specified operating period, the total energy requirement can be expressed using Equation (2) [14].

$$E_{load} = P_{total} \times t \tag{2}$$

The required photovoltaic system capacity is determined by considering the total energy demand, the available peak sun hours (PSH), and the overall efficiency of the photovoltaic system. Peak sun hours represent the equivalent duration of solar irradiance at a reference intensity of 1,000 W/m² and provide a practical basis for estimating daily photovoltaic energy generation. The overall system efficiency accounts for energy losses associated with photovoltaic conversion under operating conditions, power conditioning, electrical transmission, and other relevant system components. Accordingly, the required photovoltaic capacity is calculated using Equation (3) [15].

$$P_{\mathrm{PV}} = \frac{E_{\mathrm{load}}}{PSH \times \eta_{\mathrm{system}}} \tag{3}$$

Following the determination of the required photovoltaic capacity, the number of PV modules is calculated based on the rated power output of the selected photovoltaic module. The total installed photovoltaic capacity is obtained from the combined nominal power ratings of the individual modules. Therefore, the minimum number of photovoltaic modules required is determined using Equation (4) [16].

$$N_{\mathrm{PV}} = \left\lceil \frac{P_{\mathrm{PV}}}{P_{\mathrm{module}}} \right\rceil \tag{4}$$

The calculated value is rounded up to the nearest whole number to ensure that the installed photovoltaic capacity meets or exceeds the estimated power generation requirement.

For a PADDY-SMART configuration incorporating battery-based energy storage, the required battery capacity is determined by considering the total electrical energy demand, nominal battery voltage, allowable depth of discharge (DOD), and battery efficiency. The inclusion of an energy storage system enables electrical energy generated by the photovoltaic modules to be stored and utilized when solar irradiance is insufficient or unavailable. Appropriate battery sizing is therefore essential for maintaining operational reliability and preventing excessive battery discharge, which may adversely affect battery performance and service life.

The required battery capacity is estimated using Equation (5) [17].

$$C_{\mathrm{battery}} = \frac{E_{\mathrm{load}}}{V_{\mathrm{battery}} \times DOD \times \eta_{\mathrm{battery}}} \tag{5}$$

The calculated battery capacity provides an initial estimate of the storage requirement under the specified operating conditions. In addition to energy storage capacity, the battery system must be capable of delivering the maximum electrical power demanded by the connected loads. Therefore, battery selection should consider both energy capacity and discharge power capability to ensure compatibility with the operational characteristics of the PADDY-SMART system.

2.3 Three-Dimensional Design of the PADDY-SMART System

The three-dimensional (3D) design of the PADDY-SMART system is developed to establish the overall structural configuration, physical dimensions, component arrangement, and mechanical integration of the proposed post-harvest processing equipment before fabrication. This design stage provides a comprehensive visualization of the system architecture and facilitates the assessment of spatial requirements, component compatibility, and operational accessibility. Particular emphasis is placed on integrating the photovoltaic power supply, paddy cleaning mechanism, drying unit, and IoT-based monitoring subsystem into a compact and functionally coordinated configuration.

The arrangement of the mechanical components is developed according to the intended sequence of paddy processing operations, beginning with grain feeding, followed by impurity removal, drying, and discharge of the processed grain. This sequential configuration is intended to facilitate material movement between processing stages while minimizing unnecessary handling and operational interruptions. The positioning of the cleaning and drying units is also considered to ensure compatibility between the respective mechanisms and to support efficient material transfer throughout the system.

Three-dimensional modeling is employed to determine the locations and spatial relationships of the principal structural and functional components, including the supporting frame, photovoltaic panels, grain cleaning mechanism, drying chamber, electrical control components, sensors, and IoT communication devices. The supporting structure is designed to accommodate the mechanical and electrical components while providing adequate stability during operation. The photovoltaic panels are positioned with consideration of mounting requirements and potential solar exposure, whereas the electrical and monitoring components are arranged to facilitate installation, maintenance, and protection from adverse operating conditions.

Furthermore, the component layout is developed with consideration of assembly feasibility, operational accessibility, structural compactness, and maintenance requirements. Appropriate spacing between components is incorporated to facilitate equipment installation, inspection, and replacement without unnecessarily increasing the overall dimensions of the system. The integration of sensors and monitoring devices is also considered during the design stage to ensure that relevant operating parameters can be measured at suitable locations within the cleaning, drying, and energy supply subsystems.

The resulting 3D model serves as a technical reference for subsequent engineering calculations, material selection, component dimensioning, and fabrication planning. It also provides a basis for evaluating the compatibility of the mechanical, electrical, and monitoring subsystems before physical implementation. Through this design approach, the PADDY-SMART system is intended to achieve an integrated, compact, and practical configuration suitable for solar-powered paddy post-harvest processing.

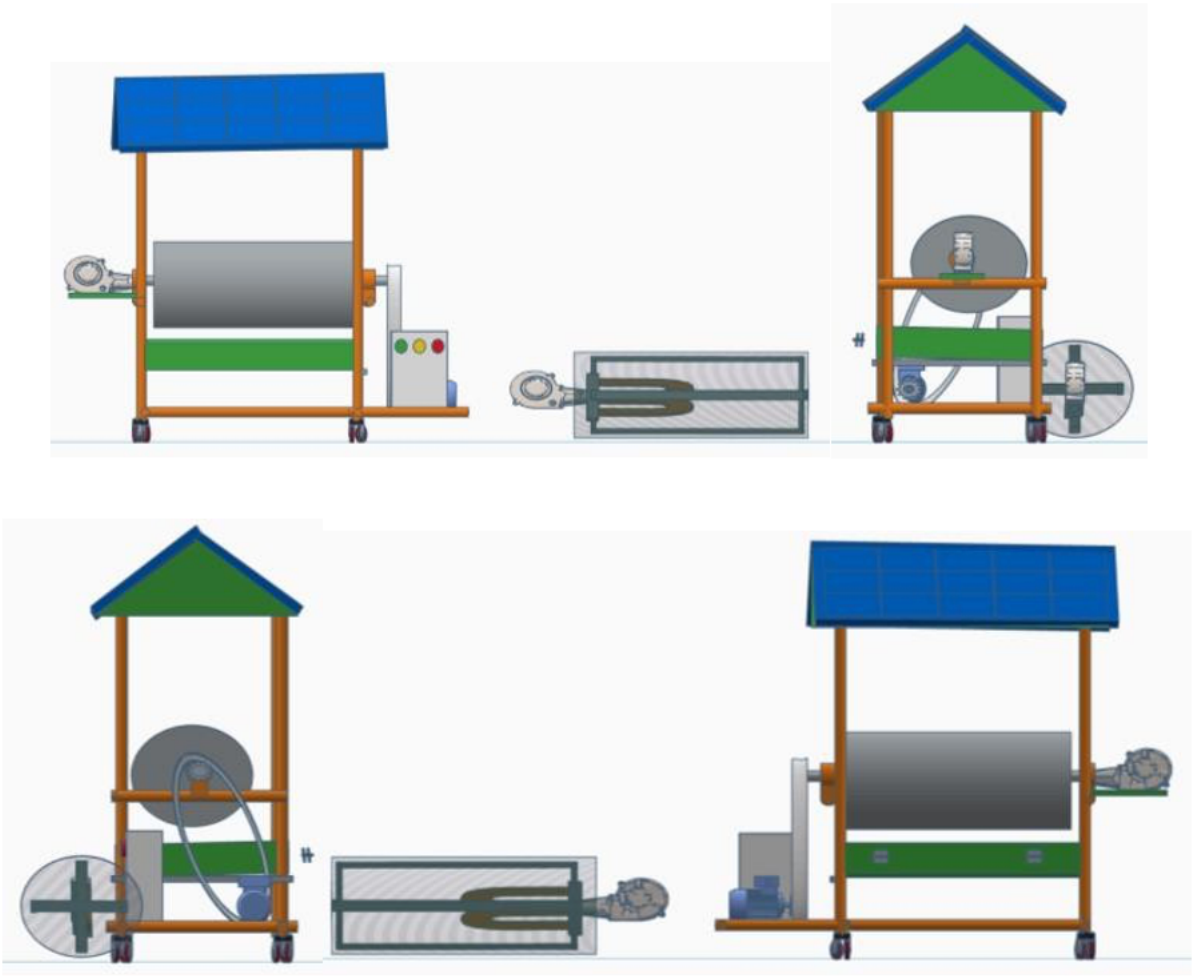


Fig. 2. PADDY-SMART three-dimensional model

Once the three-dimensional design of PADDY-SMART is compiled to describe the shape and layout of the components, the next stage is to design the electrical and monitoring system schematics. The design of this schema aims to explain the relationships between components as well as the flow of energy and data during the grain cleaning and drying process. The system schematic is also used as a reference in determining component specifications and evaluating daily energy needs. The PADDY-SMART system schematic is designed to integrate photovoltaic energy sources, energy storage, grain cleaning and drying units, and Internet of Things (IoT)-based monitoring. The system workflow begins when the photovoltaic module converts solar energy into electrical energy. The energy is then regulated by MPPT to charge a $LiFePO_4$ battery as energy storage.

Energy from the battery is channeled through an inverter to supply the AC load, namely the cleaning unit's motor, heating element, and blower in the drying unit. The motor drives the grain cleaning mechanism, while the heater produces hot air that the blower delivers to the drying chamber. If the supply from the photovoltaic system and battery is insufficient, PLN's power source can be used as a backup supply through the ATS. During the process, the sensor measures the electrical, temperature, and humidity parameters. The data is processed by the ESP32 and transmitted wirelessly to the dashboard to monitor the operating conditions of the system. The component integration flow is shown in Figure 3.

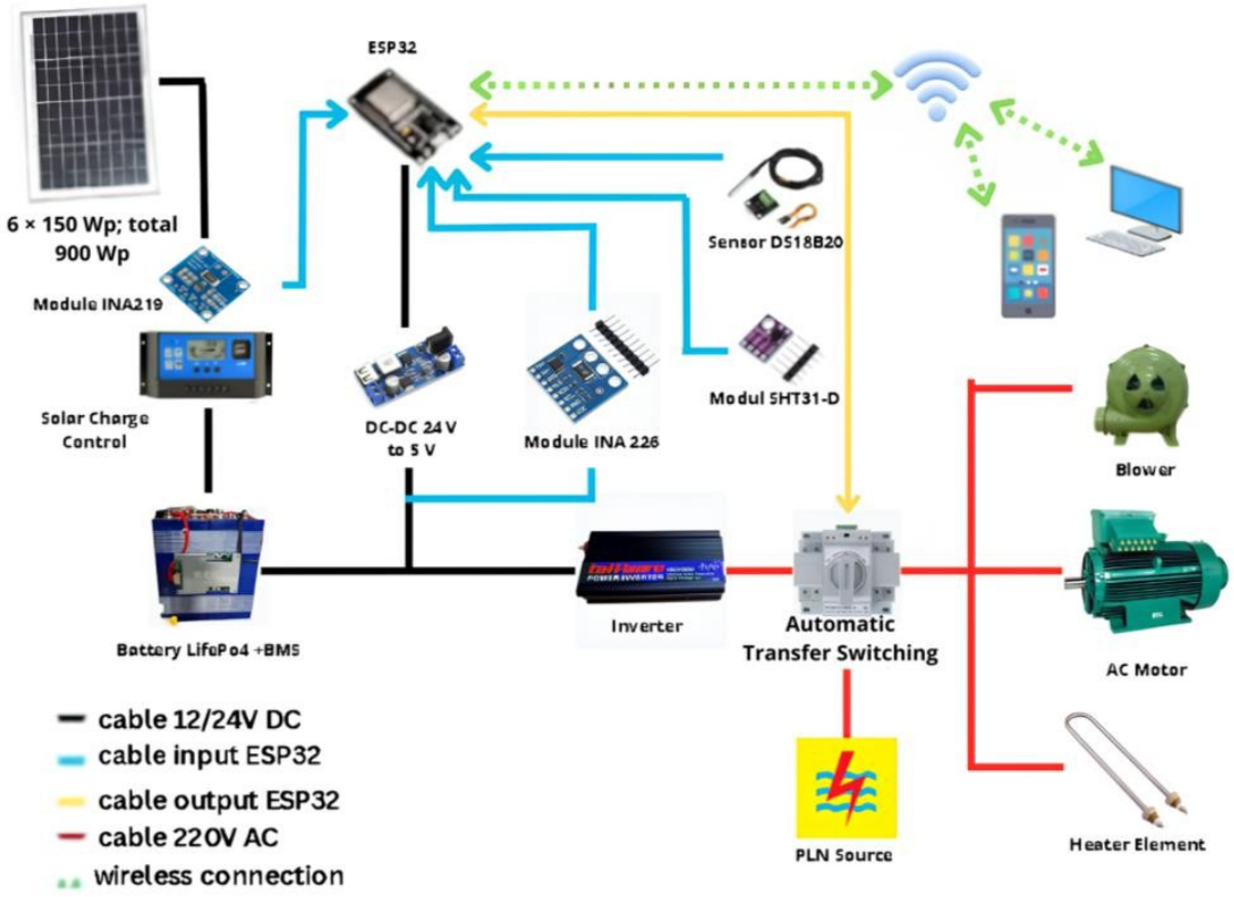


Fig. 3. PADDY-SMART Electrical and Monitoring System Scheme

To support the design of the system scheme, the component specifications and the estimated energy requirements of PADDY-SMART are summarized in the table. Table 1 presents the main components along with their design specifications and functions.

Table 1
PADDY-SMART System Design Specifications

Component	Design Specifications	Function
Photovoltaic (PV) modules	6 × 150 Wp; total installed capacity of 900 Wp	Convert solar energy into electrical energy
Solar charge controller	Maximum Power Point Tracking (MPPT), 40 A, 24 V	Regulate battery charging and optimize power extraction from the PV modules
Battery	Lithium iron phosphate ($LiFePO_4$), 24 V, 150 Ah, equipped with a Battery Management System (BMS)	Store electrical energy and provide power when solar energy is insufficient
Inverter	Pure sine wave, 2,000 W; 24 VDC/220 VAC	Convert DC power into AC power for system operation
Cleaning unit motor	250 W	Drive the mechanical paddy cleaning mechanism
Heating element	500 W	Generate thermal energy for the paddy drying process

Blower	40 W	Circulate heated air through the drying chamber
ESP32 microcontroller	Estimated IoT subsystem power consumption of 5 W	Process sensor measurements and transmit operational data to the monitoring platform
INA226 sensor	Voltage and current monitoring sensor	Measure electrical parameters for monitoring system power consumption and performance
DS18B20 sensor	Digital temperature sensor	Measure temperature during the drying process
SHT31-D sensor	Digital temperature and relative humidity sensor	Monitor temperature and relative humidity within the drying environment
DC–DC converter	24 VDC to 5 VDC	Provide regulated electrical power to IoT devices and monitoring components
Automatic Transfer Switch (ATS)	220 VAC, minimum 16 A	Automatically switch the electrical supply to a backup source when required
Backup power source	PLN (Indonesian national electricity grid)	Supply electrical power when the primary solar energy system cannot meet operational demand

3. Results

3.1 Design and Development of the PADDY-SMART System

The three-dimensional (3D) design of the PADDY-SMART system illustrates the overall structural configuration and spatial arrangement of the components integrated into a solar-powered paddy cleaning and drying system. The design provides a comprehensive visualization of the system architecture, highlighting the positioning and integration of the principal mechanical, electrical, and monitoring components within a unified configuration. To facilitate interpretation of the proposed design, each major component is identified using a numerical label corresponding to its location in the 3D model. These labels enable clear identification of individual components and their respective functions, providing a better understanding of the structural arrangement, functional relationships, and overall integration of the PADDY-SMART system.

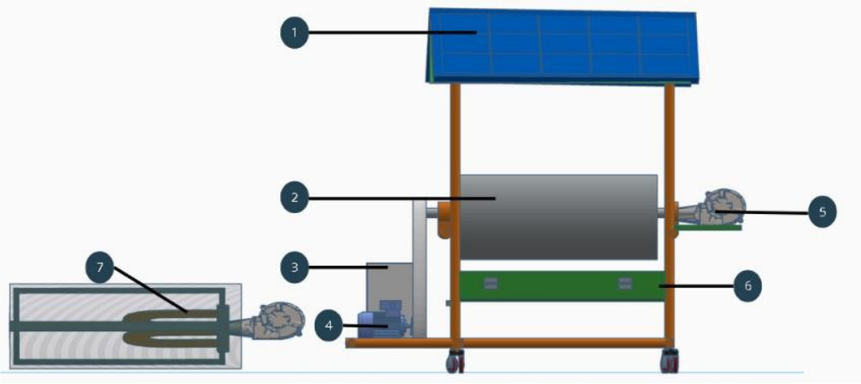
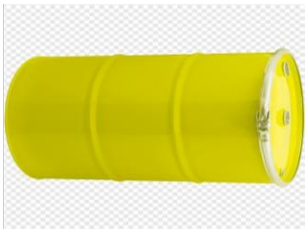


Fig.4. Design and Build the PADDY-SMART System

Table 2
PADDY-SMART System Components

No	Detail Gambar	Nama Komponen
1		Solar PV Panels
2		Paddy Drum
3		*Panel Box/Panel Control*
4		AC Motor
5		Blower
6		ignition tray

7		Electric Heating Element

The components displayed in the design have a role that supports each other in the implementation of the post-harvest process. The solar panel functions as a source of electrical energy, while the cleaning and drying unit plays a role in handling grain. Other supporting components are used to support the operation of the system, including energy supply and monitoring of working conditions. The placement of components in the three-dimensional design is also a reference to see the integration between units and estimate the space needs and layout of the system [19].

3.2 Results of Power and Energy Requirements Calculation

Based on the calculation method described in Subchapter 2.2, an evaluation was carried out on the daily power and energy needs of PADDY-SMART. This evaluation aims to determine the suitability of the capacity of photovoltaic panels and batteries to the energy needs of the cleaning, drying, and monitoring units of IoT. The results of the calculation are summarized in Table 2.

Table 3
PADDY-SMART Power and Energy Calculation Results

Parameters	Value of the Plan
Total nominal load power	795 W
Daily energy needs before inverter losses	1.91 kWh/day
Daily energy needs after inverter losses	Approx. 2.12 kWh/day
PV Capacity	900 Wp
PSH Assumptions	4.5 hours/hr
Assumptions of system performance factors	75%
Estimated PV energy production	Approx. 3.04 kWh/day
Nominal energy of the battery	3.6 kWh
Theoretical battery use energy at DOD 80%	2.88 kWh

Based on Table 3, the total nominal power demand of the PADDY-SMART system is 795 W, corresponding to an estimated daily energy consumption of approximately 1.91 kWh before accounting for inverter losses. Considering an inverter efficiency of 90% for AC loads, the total daily energy requirement increases to approximately 2.12 kWh. The photovoltaic (PV) array, with an installed capacity of 900 Wp, is estimated to generate approximately 3.04 kWh/day, assuming a peak sun hour (PSH) value of 4.5 hours/day and an overall system performance factor of 75%. Since the estimated PV energy generation exceeds the calculated daily energy demand, the proposed PV capacity is theoretically sufficient to meet the system's energy requirements under the assumed solar irradiation and operating conditions. Furthermore, the 24 V, 150 Ah $LiFePO_4$ battery provides a nominal energy storage capacity of 3.60 kWh, with a theoretical usable capacity of 2.88 kWh at a depth of discharge (DOD) of 80%. As the usable battery energy exceeds the estimated daily consumption of 2.12 kWh, the proposed battery configuration is also theoretically capable of supporting the system's daily energy requirements under the specified design assumptions [20].

Despite these preliminary findings indicating the potential adequacy of the PV array and battery storage capacity, the actual energy performance of the PADDY-SMART system will depend on several factors, including variations in solar irradiation, component efficiency losses, operating duration, and load characteristics. In particular, the inverter capacity must be evaluated against the motor's starting current and transient power requirements to ensure reliable operation. Similarly, the ratings and specifications of the maximum power point tracking (MPPT) charge controller, battery management system (BMS), electrical cables, and protection devices must be appropriately matched to the selected system components. It is important to emphasise that the values presented in Table 2 are derived from preliminary design calculations and assumed operating parameters rather than direct experimental measurements obtained from a physical prototype.

4. Conclusions

This study presents the conceptual design of PADDY-SMART, an integrated solar-powered grain cleaning and drying system incorporating Internet of Things (IoT)-based monitoring capabilities. The proposed system integrates photovoltaic panels, battery energy storage, grain cleaning and drying units, and a digital monitoring platform to support more efficient and potentially scalable post-harvest operations. Based on preliminary energy calculations, the system incorporates a 900 Wp photovoltaic array, a 24 V, 150 Ah $LiFePO_4$ battery, a 40 A MPPT charge controller, and a 2,000 W inverter. Assuming 4.5 peak sun hours per day and an overall system performance factor of 75%, the estimated daily PV energy generation is approximately 3.04 kWh. Meanwhile, the battery provides a theoretical usable energy capacity of 2.88 kWh at an 80% depth of discharge. These preliminary calculations indicate that the proposed PV and battery capacities have the potential to satisfy the estimated daily energy demand of 2.12 kWh under the specified design assumptions.

The proposed ESP32-based monitoring system, integrated with appropriate sensors, is designed to continuously monitor electrical parameters, temperature, and humidity during system operation. The collected data are intended to facilitate operational monitoring, support performance assessment, and provide information for evaluating the effectiveness of the grain cleaning and drying processes. Nevertheless, the adequacy of the proposed energy configuration and the overall operational performance of PADDY-SMART remain to be validated through numerical simulations and experimental prototype testing. Particular attention should be given to variations in solar irradiation, actual operating duration, motor starting current, component efficiency, and load characteristics under practical operating conditions. Overall, PADDY-SMART demonstrates potential as an integrated post-harvest grain processing solution that combines renewable energy utilisation with digital monitoring technologies. Future research should prioritise validation of the proposed system design, experimental assessment of grain cleaning and drying performance, and comprehensive evaluation of energy consumption and system reliability under actual operating conditions.

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