

DESIGN AND POTENTIAL OF A HYBRID BIOGAS REACTOR WITH SOLAR PANELS FOR ENERGY CONVERSION IN TROPICAL AREAS

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ABSTRACT

Improperly managed cow dung can pollute the environment, causing unpleasant odors and contaminating groundwater. Therefore, a portable biogas reactor with a floating digester model was designed to process the waste into biogas energy and organic fertilizer while reducing the impact of pollution. The design method used the Pahl and Beitz approach, starting from task clarification to design development, focusing on portability, efficiency, and ease of operation. The reactor was designed to be able to process up to 300 kg of waste per month and was equipped with solar panels as an alternative energy source to operate the heating agitator and sensors, making it suitable for use in areas with minimal electricity access. The system was tested based on the daily performance of photovoltaic PV from 7:00 am to 6:00 pm. Based on the results of observations, a typical pattern of the PV system with the highest performance occurred when the light intensity was maximum at 12:00 pm. This hybrid system and reactor has the potential to be a sustainable solution in livestock waste management and support environmentally friendly agricultural practices.

Keywords: Biogas Reactor, Photovoltaic, Hybrid System, Livestock Waste Management, Pahl and Beitz.

1. Introduction

Cow dung is one of the largest organic wastes produced by the livestock sector in Indonesia, particularly in rural areas. On average, one cow produces dung every month (Kariyat & Janardhanan, 2023). However, the waste that is utilized effectively is still minimal and is simply thrown away without further processing (Miehle et al., 2021), (de Nooijer et al., 2018). This has various negative impacts on the environment, such as air pollution due to pungent odors, as well as contamination of ground and surface water due to runoff of organic substances and pathogens. (D'Bastiani et al., 2023), (Banerjee et al., 2021), (Ongis et al., 2023). In fact, cow dung waste has a high organic content, including nitrogen, phosphorus, and carbon, which has great potential to be processed into biogas and solid and liquid organic fertilizer through an anaerobic fermentation process (Jeppu et al., 2022), (Vogel et al., 2023). If managed optimally, this waste can be reduced annually for each cow, while also producing alternative energy that can be used for household needs and small-scale production activities (Sun et al., 2024), (Dalkilic & Ugurlu, 2024), (Del Pópolo Grzona et al., 2024).

However, the biogas processing technology currently available in the field is generally still conventional, expensive, and requires high technical skills, so it is less suitable for application to small- to medium-scale livestock farms (Silva et al., 2024), (Arthur et al., 2022). As a response to these problems, it is necessary to develop a technological innovation in the form of a portable biogas reactor that is simple, cheap, easy to operate, and efficient in terms of cost and efficiency (Bakraoui et al., 2020), (Wongfaed et al., 2021). This type of reactor is designed using the principle of a floating digester system which is flexible, space-saving and can be moved as needed

(Hackula et al., 2024), (Mary et al., 2024). This technology is expected to be a strategic solution in community-based livestock waste management, while empowering villagers to be more independent in providing environmentally friendly and sustainable energy (Rahimi et al., 2024), (Tommasi et al., 2024).

Apart from the use of biogas, another very promising renewable energy potential in Indonesia is the Photovoltaic system (PV) (Satria et al., 2023), (Li et al., 2023), (Liu et al., 2022). Indonesia as a tropical country with high intensity of sunlight has ideal climate conditions for implementing this technology (Alsagri, 2022), (Sutanto et al., 2024). The increasing population and the ever-growing energy needs encourage the importance of developing decentralized PV-based energy systems, especially with a stand-alone system approach for areas that are not yet connected to electricity by the main grid (Sampaio & González, 2017), (Lillo-Bravo et al., 2023). Besides being environmentally friendly and emission-free, the PV system is also able to utilize existing land without requiring investment in new land, making it ideal for application in remote settlements or agricultural land (Pastuszak & Węgierek, 2022). The integration of portable biogas reactors and PV systems creates a comprehensive, adaptive, and applicable renewable energy ecosystem for rural communities (Rika Rosnelly, 2024), (Gutiérrez-Martín et al., 2024). This model not only offers waste management and energy supply solutions, but also contributes to climate change mitigation strategies through reducing greenhouse gas emissions, increasing local energy independence, and creating economic added value based on appropriate technology (Hussien et al., 2023).

While previous studies have explored fixed-dome biogas reactors (Spodoba et al., 2025), (Rodrigues Oliveira et al., 2024), (Prem et al., 2023) and standalone PV systems for rural electrification (Shukla et al., 2024), (Nkempi et al., 2023), (Reddy & Reddy, 2024), there is a significant research gap in the integration of these two technologies for autonomous, portable waste management. Existing portable digesters often suffer from low gas yield due to inconsistent slurry temperatures. This study introduces a novel hybrid configuration where a PV-powered heating agitator is integrated to optimize anaerobic digestion, providing a self-sufficient energy solution for remote livestock areas. Thus, this approach is expected to become an innovative prototype for the development of independent energy villages based on sustainable local resources.

2. Research Methods

This research focuses on the design of a portable biogas reactor for processing cow manure and solar photovoltaics (PV) as a supplemental source of solar-generated electricity. This study employs a quantitative experimental design integrated with the Pahl and Beitz engineering framework. The design process was executed in four systematic phases:

a. Task Clarification

Defining requirements for a portable system capable of processing 300 kg of manure per month with autonomous power.

b. Conceptual Design

Selecting the floating digester model over the fixed-dome model for pressure stability and portability.

c. Embodiment Design

Determining material specifications (fiberglass and HDPE) and calculating the scale-up from 1.5 m³ capacity.

d. Detail Design

Finalizing the 16 integrated components, including the PV-powered agitator and sensor monitoring system.

For PV, data was collected directly in the morning from 7:00 a.m. to 6:00 p.m. Secondary data was obtained from a documentation study related to the site's background and supporting scientific references. The sampling technique used was saturated sampling, where the entire population was used as respondents due to its relatively small size. The independent variables in this study included cow dung, community complaints, user aspirations, and the limitations of currently available waste treatment technologies. The dependent variable was the design of a

portable biogas reactor aimed at managing cow dung more efficiently and sustainably. The formula used in this study to produce biogas in the reactor is as follows:

$$P = \frac{1}{T} \int_0^T u(t) \times i(t) dt \quad (1)$$



Equation (1) for the Power of the Biogas Energy Conversion Reactor, Equation (2) Methane Formation through CO₂ reduction by H₂, Equation (3) decarboxylation of acetic acid and Equation (4) Methane Combustion. Furthermore, the potential location for installing portable biogas reactors and photovoltaics that will be developed is based on Figure 1.

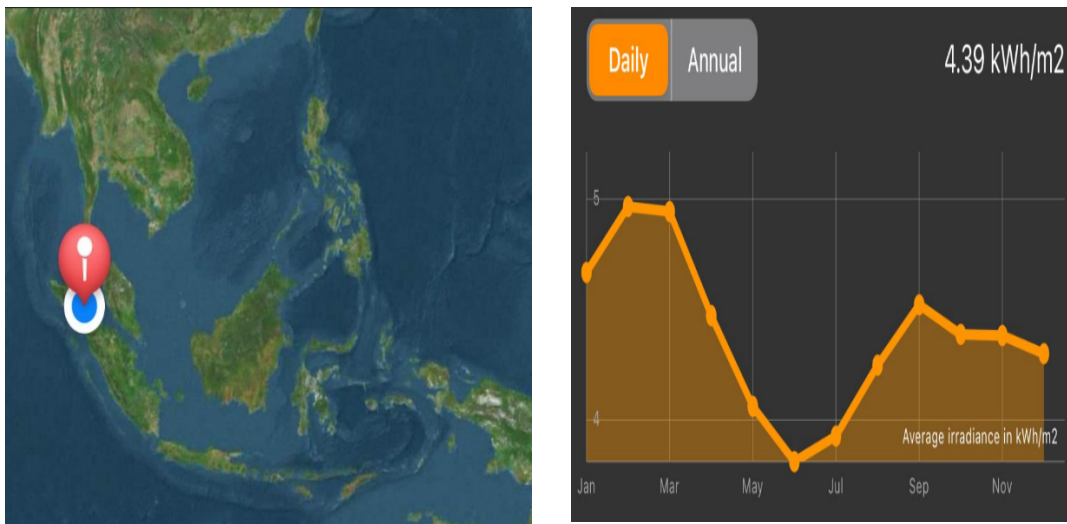


Fig 1: Portable Biogas Reactor and Photovoltaic Installation Locations

After the potential installation location for the portable biogas reactor and photovoltaic unit was allocated, a concept planning stage was conducted based on considering basic specifications through a questionnaire, then reorganized into a closed questionnaire to identify user needs in a structured manner. Therefore, a portable biogas reactor made of corrosion-resistant fiberglass was needed, with a fermentation tank, equipped with a drain valve, gas outlet pipe, and safety valve. The maximum dimensions of 1.5 m³ were designed for ease of transportation and efficiency, capable of accommodating 300 kg of waste per month, with a fermentation time of 3–4 days. The float tank was made of HDPE and fiberglass, lightweight and durable for up to 5 years. In the embodiment design stage, the main components included an HDPE/metal fermentation drum, a gas storage tank, a sealed cover, and a PVC piping system for material inlet and outlet. The gas valve was made of stainless steel, while PVC connections and elbows ensured flow in the designed direction. The final stage produced complete design drawings with dimensional specifications and 3D visualizations from various angles, which showed the integration of all reactor components to ensure optimal function and efficiency. The design of the portable biogas reactor and photovoltaic equipment is shown in Figure 2 below.

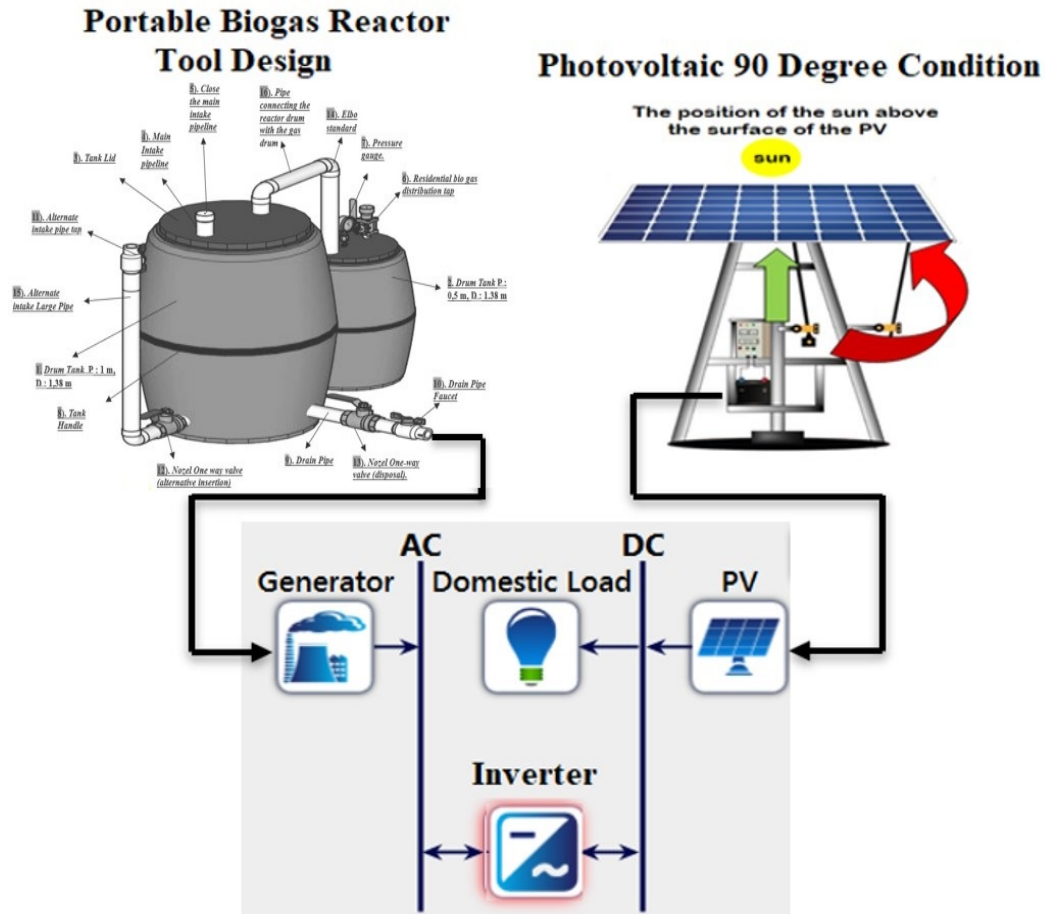


Fig 2: Design of Portable Biogas Reactor and Photovoltaic Equipment

The main components in the design of this portable biogas reactor consist of several elements designed to support the efficiency and effectiveness of the livestock waste processing system consisting of component 1) Drum Tank P 1 m, D 1.38 m, and component 2) Drum Tank P 0.5 m, D 1.38 m functions as the main and backup place for the organic waste fermentation process. component 3) Drum/tank cover is used to tightly close the drum, ensuring that the fermentation process takes place under optimal anaerobic conditions. component 4) Main inlet pipe flows organic material into the drum, while component 5) Main inlet pipe cover ensures there are no leaks or disturbances in this line. component 6) Biogas distribution valve to the house functions to flow the fermented gas to the energy utilization system such as a biogas stove or generator. component 7) Pressure gauge is installed to monitor the pressure inside the drum, ensuring there is no excess pressure that can damage the system. component 8) Tank handle makes it easy to move the drum, both empty and full, for easy maintenance or emptying. Component 9) Drain pipe and Component 10) Drain pipe valve are used to discharge residual liquid produced during the fermentation process. Component 11) Alternative inlet pipe valve provides a backup path to enter liquid organic material without disrupting the ongoing fermentation process. Component 12) One-way valve nozzle (alternative inlet) and Component 13) One-way valve nozzle (exhaust) function to ensure that only organic material enters and exits, preventing the entry of outside air that can disrupt the anaerobic fermentation process. Component 14) 3 pcs standard Elbo allows the direction of pipe flow to be adjusted as needed, and Component 15) Large alternative inlet pipe is used to channel liquid material into the drum efficiently. Finally, Component 16) The connecting pipe between the reactor drum and the gas drum connects the fermentation drum with the gas storage drum, ensuring a smooth and safe flow of biogas for further utilization. All of these components work together to support the livestock waste processing process efficiently, safely, and environmentally friendly. Meanwhile, for PV, a solar tracking system is used to carry out a hybrid system to the integrated load on the biogas reactor.

3. Results and Discussions

During the detailed design phase of the portable biogas reactor, several additional components were added to optimize the device's performance. These components include an alternative inlet pipe, a pressure gauge, a large valve (ball valve), one-way valve nozzles on the discharge valve and the alternative pipe, and a liquid discharge valve. The alternative pipe allows the introduction of liquid organic material without disrupting the ongoing fermentation process, using large-sized PVC. The pressure gauge monitors the gas pressure in the drum, preventing excessive pressure that could damage the system. The large valve facilitates the introduction of large volumes of liquid material, while the one-way nozzle prevents the ingress of outside air, maintaining anaerobic conditions. A standard elbow is used for flexibility in flow direction, and a drum handle is added for easy transportation. These additions improve fermentation stability, gas production consistency, residue disposal efficiency, as well as ease of maintenance and operational safety.

a. Biogas Reactor Analysis

A comparative analysis shows significant improvements in efficiency, flexibility, and safety, making it suitable for small- to medium-scale applications. The reactor begins with the collection of fresh cow dung, mixed with water to form a slurry, and then fed into the digester through an inlet pipe. The anaerobic fermentation process lasts for 3 to 4 days, producing biogas that can be used for stoves or generators. A pressure gauge is used to monitor pressure to ensure optimal operation. The fermentation residue can be used as liquid or solid fertilizer. This reactor is capable of processing 300 kg of waste per month and producing approximately 60 kg of gas, contributing to the availability of alternative energy at the local level.

b. Photovoltaic Output Data Analysis

This data is the result of daily performance observations of the photovoltaic (PV) system from 7:00 AM to 6:00 PM, which includes six main parameters, namely voltage at maximum power point (V_{mp}), maximum current (I_{mp}), maximum power (P_{MP}), open circuit voltage (V_{oc}), short circuit current (I_{sc}), and idle power ($Idle\ Power$). In general, all parameters show a typical pattern of the PV system, namely increasing performance as light intensity increases in the morning, reaching a peak at noon, and then decreasing in the afternoon. The results of the Photovoltaic measurement output are shown in Figure 3 below.

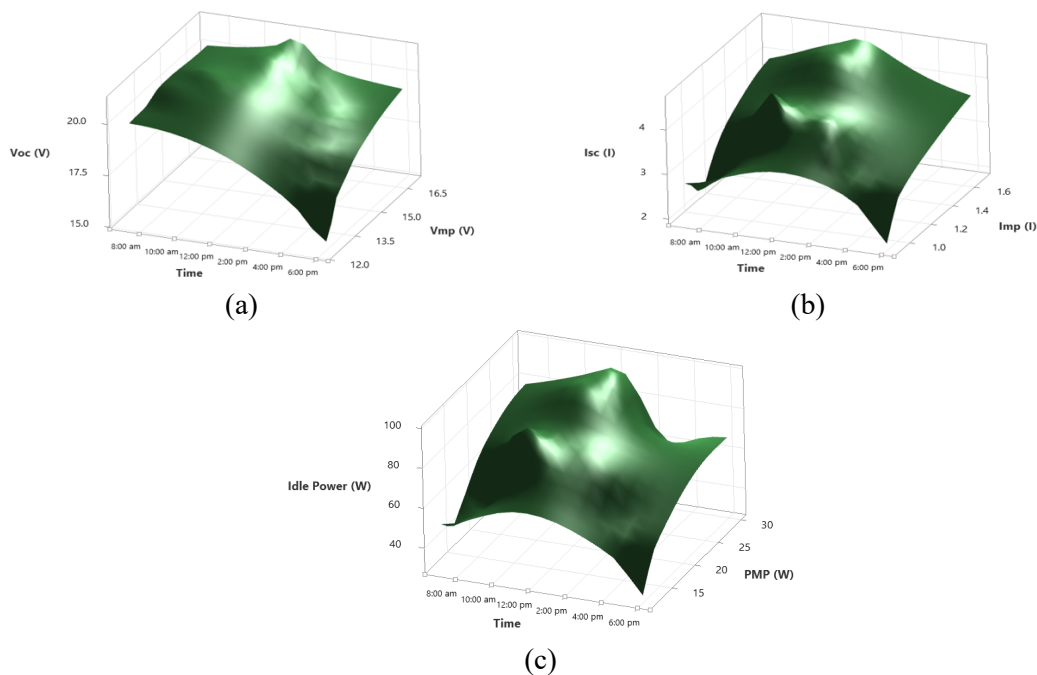


Fig 3. Effect of PV/T output in converting energy; (a) DC voltage without load (V_{oc}) and load (V_{mp}), (b) current without load (I_{sc}) and load (I_{mp}), and (c) power without load (W_p) and burdened (W_p)

Based on Figure 3, the voltage value V_{mp} experienced a gradual increase from 13.20 V at 7:00 am and reached a maximum value of 17.02 V at 12:00 pm, then decreased again to 12.50 V at 6:00 pm. V_{oc} showed a similar trend, with an increase from 19.72 V to a maximum of 21.00 V, before finally decreasing sharply to 15.30 V. The maximum current (I_{mp}) and short circuit current (I_{sc}) also followed a consistent up-and-down pattern. I_{mp} increased from 1.05 A to 1.70 A during the day, and then decreased to 0.90 A. I_{sc} experienced a significant increase from 2.20 A to 4.60 A, then decreased to 2.01 A towards the afternoon. This pattern reflects the direct influence of solar radiation intensity on the performance of the PV system. The PMP parameter as a representation of maximum power shows a trend that is highly dependent on the combination of V_{mp} and I_{mp} . Power increased from 13.86 W to 28.93 W at 12:00 pm, which is the daily peak performance. Meanwhile, Idle Power increased from 43.38 W in the morning to 96.06 W at noon, and then decreased to 30.75 W in the afternoon. This pattern indicates that even though the main output decreases, the system still consumes latent power for internal operations or monitoring loads. Overall, this data pattern forms an inverted parabola curve, which is characteristic of PV systems against daily operating time (Liu et al., 2025), (Al Humairi et al., 2024), (Han et al., 2026), (Qu et al., 2024).

The integration of the PV system in this design directly supports the operational efficiency of the biogas reactor through the provision of independent energy. (Tercha et al., 2024), (Alao et al., 2025), (Patil, 2024), (Zhang et al., 2024). The electrical energy generated from the solar panels is used to drive the DC motor agitator unit and supply power to the pressure monitoring sensor continuously (Vinay Anand, Himanshu Sharma, 2024), (Ahmed et al., 2025), (Alasali et al., 2024). This hybrid synergy ensures that the cow dung slurry in the digester remains homogeneous, which is a crucial factor in optimizing the interaction of anaerobic microorganisms and preventing the formation of scum on the surface of the liquid (Anand & Kumar, 2025). The automatic solar-powered agitation ensures a more stable organic material degradation process compared to conventional digesters that rely on manual agitation. This integrated model demonstrates that solar energy utilization serves not only as a supplemental resource but also as a core component that ensures the sustainable operation of biogas reactors in locations with limited access to grid electricity. These findings can be used to determine optimal operating time, maximize energy production, and develop maintenance and system efficiency strategies based on empirical data. Then, the data is extracted into a visualization of the main effects of time on the photovoltaic system output on V_{mp} , I_{mp} , and PMP as shown in Figure 4.

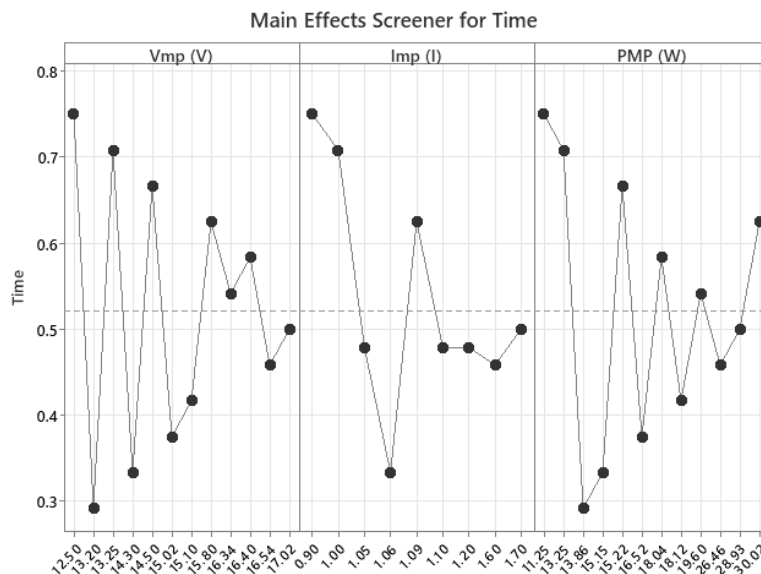


Fig 4. Visualization of the Main Effects of Time on Photovoltaic System Output: V_{mp} , I_{mp} , and PMP

Based on Figure 4, the results of the Main Effects Screener for Time analysis illustrate the influence of three main variables in a photovoltaic (PV) system over time: V_{mp} (maximum

voltage), Imp (maximum current), and PMP (maximum power). Figure 4 presents a visualization in the form of a scatterplot grouped by variable, with a horizontal dotted line as a marker of the average value, making it easier to identify trends and anomalies in PV system operation over time. The Vmp variable shows high fluctuations between 0.3 and 0.75, indicating external influences such as module temperature or varying solar irradiation intensity. Imp tends to be more stable but still shows significant variations, which are most likely influenced by system load or extreme weather conditions. Meanwhile, PMP, as the product of Vmp and Imp, represents the maximum power that the system can produce. The PMP graph shows the combined fluctuation pattern of the two previous variables and provides a direct picture of changes in PV system efficiency. Then, for a visualization of the main effects over time on the voc, isc, and idle power parameters of the PV system, is shown in Figure 5.

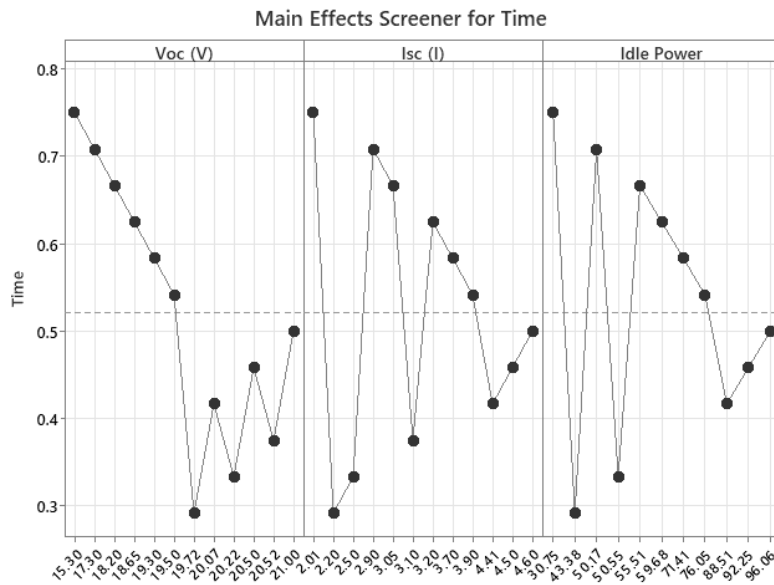


Fig 5. Visual Analysis of the Main Effects of Time on the Parameters Voc, Isc, and Idle Power of Photovoltaic Systems

The visualization in Figure 5 shows the results of the Main Effects Screener for Time, which was used to analyze the effect of time on three key parameters of the photovoltaic system: open-circuit voltage (Voc), short-circuit current (Isc), and idle power (Idle Power). The Voc parameter shows a progressive decrease from its highest value to a minimum around 20:15, before slowly increasing again. This pattern reflects the decline in light intensity towards evening and the possible influence of artificial lighting or measurement anomalies. Meanwhile, the Isc value shows sharp and extreme fluctuations, indicating inconsistent solar irradiation, such as due to sudden cloud cover. This indicates that the current is highly sensitive to direct environmental changes. The third parameter, Idle Power, also shows consistent cyclic fluctuations. Changes in power values while the system is inactive can indicate latent power consumption from system components such as inverters or monitoring devices, as well as indicate potential power losses in the form of phantom loads. This irregularity can be an important indicator of energy efficiency and system management. Theoretically, Voc and Isc are two key parameters in the I-V characteristic curve of a photovoltaic module. Meanwhile, Idle Power, although often overlooked, plays a crucial role in evaluating the overall efficiency of a system. Performance data were extracted from the time-to-Voc, Isc, and Idle Power relationships in a PV system using a scatterplot screener based on Figure 6.

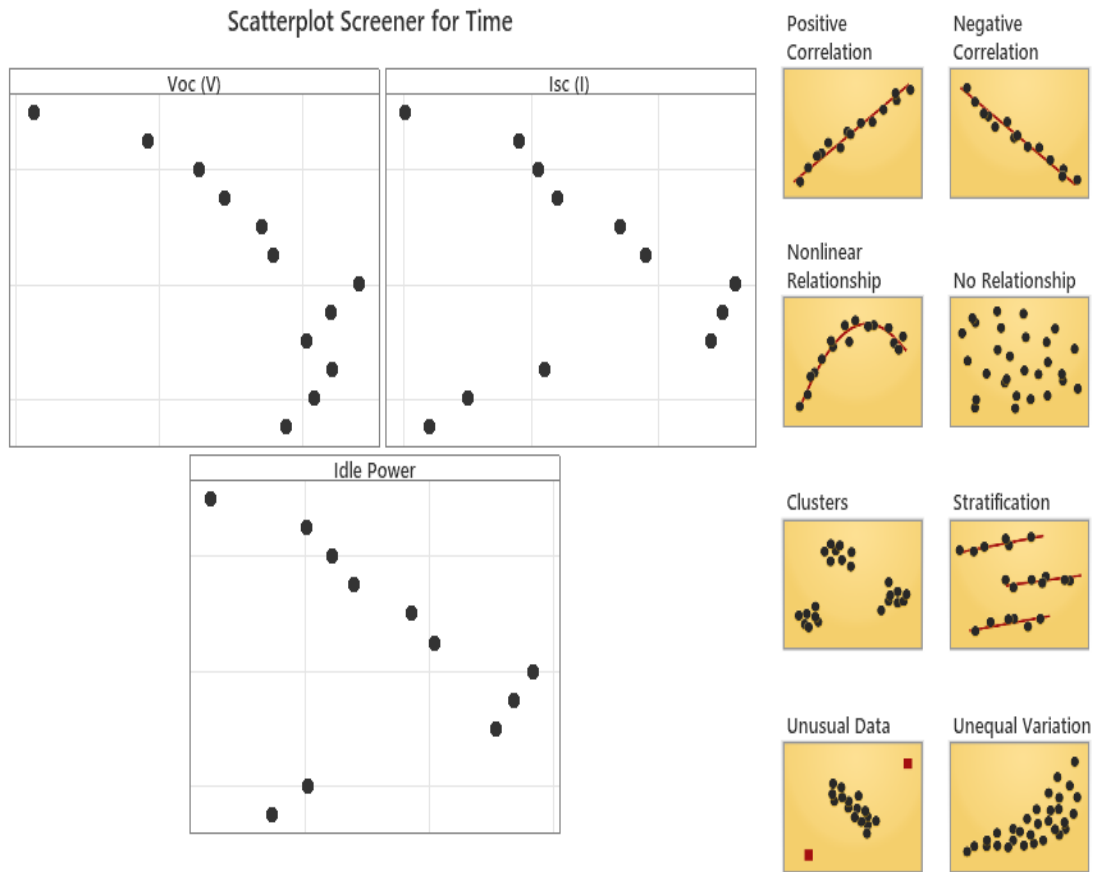


Fig 6. Analysis of the Relationship between Time and Voc, Isc, and Idle Power in Photovoltaic Systems Using Scatterplot Screener

The visualization in Figure 6 displays the relationship between time and three key photovoltaic (PV) system parameters: open-circuit voltage (Voc), short-circuit current (Isc), and idle power (Idle Power). Each scatterplot represents the values of these variables over time, with the goal of identifying patterns of correlation and variation. On the right side of Figure 6, an interpretive guide is provided covering various types of statistical relationships, such as positive correlation, negative correlation, nonlinear relationships, no relationship, clustering, stratification, unusual data, and uneven variation. The Voc scatterplot analysis shows a strong negative correlation pattern with time. Voltage values decrease consistently, reflecting the effect of increasing temperature or decreasing solar irradiance towards evening. Meanwhile, the scatterplot for Isc also shows a negative correlation, but with a slight nonlinear pattern at the end. This may indicate sudden fluctuations in light intensity that affect the stability of the output current.

For the Idle Power parameter, the scatterplot shows a nonlinear relationship pattern in the form of an upward-opening parabola. Idle power values decrease to a low point, then increase again. This pattern indicates that the PV system undergoes a transition between an active phase (when generating power) and an idle phase (when not in use), which affects the magnitude of the recorded latent power. This phenomenon is important for understanding the overall system efficiency and the potential for phantom load when there is no active energy production. The output data on the predictive ability of time parameters on Voc, Isc, and Idle Power in the PV system is shown in Figure 7.

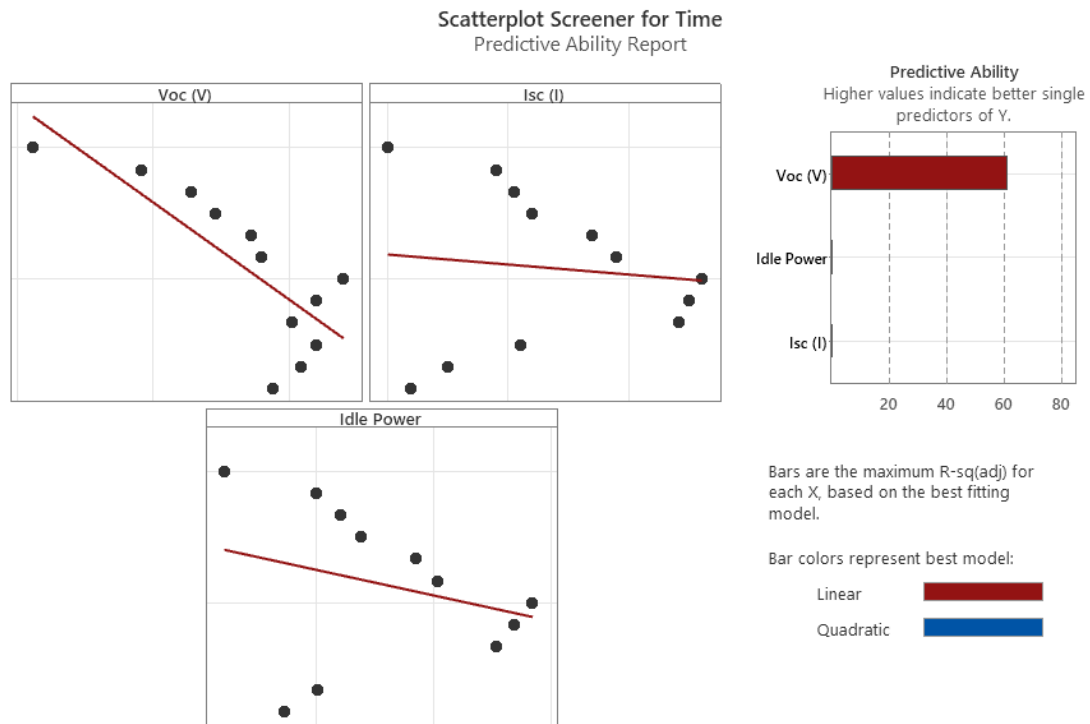


Fig 7. Analysis of the Predictive Ability of Time Parameters on Voc, Isc, and Idle Power in Photovoltaic Systems

The visualization in Figure 7 is the result of the Scatterplot Screener for Time, complemented by the Predictive Ability Report. The goal is to evaluate the extent to which three key parameters in a photovoltaic system—open-circuit voltage (Voc), short-circuit current (Isc), and idle power (Idle Power)—can be predicted based on time. Each subplot shows a scatterplot pattern complemented by the best-fit trendline (based on a linear or quadratic model), while the right side of the graph displays the adjusted R^2 values as an indicator of each parameter's predictive ability. For Voc, a strong negative correlation with time is observed, indicated by a sharply decreasing linear trendline. This indicates that Voc decreases significantly over time, reflecting a decrease in irradiance or an increase in module temperature, depending on the characteristics of the solar panel. Voc has the highest adjusted R^2 value, indicating that open-circuit voltage is the most robust and stable indicator over time. In contrast, Isc exhibits a weaker negative relationship, with a greater spread in the data and a flatter trendline. This shows that although the current tends to decrease, the relationship with time is not very consistent, making Isc a less accurate predictor of time.

Meanwhile, the Idle Power parameter shows a similar negative relationship, but with a more random distribution of data. Its predictive value is also relatively low, indicating that idle power is more influenced by system operational factors, such as inverter mode or load status, than by time itself. The bar graph on the right side confirms that the linear model is the best approximation for all variables, with Voc being the only parameter with significant predictive ability over time. Theoretically, this finding aligns with the solar energy literature, where Voc is known to be highly sensitive to temperature, while Isc is more dependent on irradiation intensity. Thus, Figure 7 provides empirical evidence that Voc can be used as a more effective indicator of photovoltaic system performance over time than other parameters.

5. Conclusion

This portable biogas reactor design successfully addresses the challenges of cow dung waste management with a waste reduction capacity of up to 2,370 kg per year and biogas production of 60 kg per month. The application of the Pahl and Beitz method has proven effective in producing a system that meets technical aspects, portability, and energy conversion efficiency.

Simultaneously, the integration of the photovoltaic (PV) system shows optimal performance with an inverted parabolic curve pattern, where the peak power reaches 28.93 W during the day. The synergy between the PV system and the biogas reactor not only ensures the system's independent operation without relying on grid electricity but also contributes to accelerating the renewable energy transition in the small-scale livestock sector. As a recommendation for further research, the development of an IoT-based intelligent control system can be applied to monitor gas quality in real-time and optimize thermal insulation materials in the digester to maintain stable fermentation temperatures in various weather conditions.

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