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Process Performance of the Arenga Sap Vacuum Evaporator using a Solar Panel as a Single Power Source

Daman Huri[1], Erwin[1,2*], Hendra[1], Slamet Wiyono[1,2], Iqbal Maulana[1,2]
[1]Mechanical Engineering, Universitas Sultan Ageng Tirtayasa, Cilegon, Indonesia
[2]Renewable Energy and Design Laboratory, Universitas Sultan Ageng Tirtayasa, Cilegon, Indonesia
***Correspondence email**: erwin@untirta.ac.id*

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Abstract: Traditional processing of Arenga sap still faces significant challenges, particularly long heating duration and high energy consumption. This study aims to evaluate the performance and energy efficiency of a solar-powered vacuum evaporator for the concentration of Arenga sap. The solar energy system consists of monocrystalline panels, an MPPT charge controller, a deep-cycle battery, and an inverter as the primary power source for the vacuum pump and induction heater, while thermal insulation is applied to minimize heat loss during evaporation. The performance test was conducted using 40 kg of fresh Arenga sap under a vacuum pressure of –0.71 to –0.73 bar and an operating temperature of 34–41°C for 150 minutes, resulting in 1.10 kg of evaporated mass. Based on the corrected and consistent dataset, the evaporation rate was calculated as 0.44 kg/hour, and the energy analysis using the latent heat of vaporization yielded an overall system efficiency of 83%. The novelty of this research lies in the implementation of a fully solar-powered low-pressure vacuum evaporator equipped with thermal insulation to enhance thermal stability. The findings indicate that this system can operate independently and offers a practical solution for small-scale Arenga sap producers, especially those located in remote or off-grid areas.

Keywords: vacuum; evaporator; Arenga; efficiency; thermal



SDGs Problem Solving

The research supports SDGs Chapter #7 by creating a completely solar-powered vacuum evaporator for Arenga sap processing. It enhances energy efficiency 81–85%, diminishes reliance on fossil fuels, and facilitates sustainable, off-grid agro-industry in rural regions via renewable energy integration.

Conflict of Interest Statement: The author(s) declares that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

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Conflict of Interest STATEMENT
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1. INTRODUCTION

Palm sap is one of the important commodities in Indonesia's traditional food industry. Its derivative products, such as printed sugar, ant sugar, and liquid palm sugar, rely heavily on the sap condensation process which takes a long time and high energy consumption (Victor, 2015). In the open heating process, sap concentration generally takes 10–12 hours (Erwin, Wiyono and Maulana Yusuf, 2024) for one production cycle so that the working efficiency of small producers becomes low and the quality of the product often fluctuates due to temperature instability during cooking (Ambarita, 2016; Al-Obaidi *et al.*, 2025). This condition is a serious challenge, especially for rural communities who have limited access to energy and more modern processing equipment.

Vacuum evaporator technology offers a more efficient approach as evaporation can take place at lower temperatures when the chamber pressure is lowered (Wiyono, Erwin and Abdullah, 2021). A number of studies have shown that reducing pressure lowers the boiling point of liquids so that the risk of thermal damage to sensitive components in sap can be minimized (Wiyono *et al.*, 2022; Yusuf *et al.*, 2023). In addition, the utilization of induction heaters and the installation of thermal insulators have been proven to improve heat stability and reduce energy losses during the process (Listijorini and Wiyono, 2019). Nonetheless, most vacuum evaporator systems that have been developed still rely on grid electricity supplies or fossil fuel generators (Asghar *et al.*, 2020). This application is less suitable for palm sap producers in remote areas that are not connected to the power grid, and increases operational costs through the use of additional fuels (Aripin *et al.*, 2018).

A very clear research gap emerges from these conditions: to date there have been few, and almost none, studies specifically designing, building, and evaluating fully solar-powered vacuum evaporators for palm sap processing. Most studies related to vacuum evaporation only examine the performance of tools in the laboratory using a fixed power supply or applied to other foodstuffs that do not reflect the typical thermal characteristics of palm sap (Djohan and Meenune, 2021). In fact, the use of solar power as a single resource has the potential to result in a food processing system that is self-sufficient, energy-efficient, and can be operated by small producers without dependence on external infrastructure.

Based on these gaps, this research makes two main contributions. First, the study developed an integrated system that combines solar panels, MPPT controllers, deep-cycle batteries, inverters, induction heaters, thermal insulators, and vacuum chambers in a single portable evaporator device that can operate completely without grid electricity. Second, this study presents a comprehensive experimental measurement of evaporation rate, thermal stability, power consumption, and energy efficiency so that the performance of the system can be assessed quantitatively (Sarkar *et al.*, 2023; Nursalam, 2024; Puspitasari, Nurhalisah and Sugmawati, 2025). The findings not only enrich the literature on renewable energy-based vacuum evaporation technology (Lourentius and Ayucitra, 2023), but it also offers a practical solution for small-scale palm sap producers who face limited energy and infrastructure access in rural areas (Djohan and Meenune, 2021).

2. METHODOLOGY

This study uses an engineering experiment method with the aim of evaluating the performance of palm sap vacuum evaporators that use solar panels as a single energy source and analyzing energy

efficiency during the evaporation process (Erwin, Wiyono and Maulana Yusuf, 2024). The research was carried out at the Renewable Energy & Design Laboratory (RED Lab) of Sultan Ageng Tirtayasa University with stages including solar power system design, integration of vacuum evaporator units, installation of thermal insulators, manufacture of automatic control systems, and performance testing of tools using 40 kg of palm sap liquid (Aripin *et al.*, 2018; Jayanudin, Kurniawan and Kustiningsih, 2019).

2.1. System Design

This study uses a solar-powered vacuum evaporator system consisting of an energy subsystem and an evaporation subsystem (see Figure 1). Energy subsystems include total capacity monocrystalline solar panels 400 Wp, charging controller MPPT battery 12 V 100 Ah, as well as a full-capacity inverter 1000 W. The electrical energy from the battery is used to operate the induction heater at average power ≈515 W and vacuum pump with operating power ≈480–500 W. Power consumption is recorded using a digital power meter.

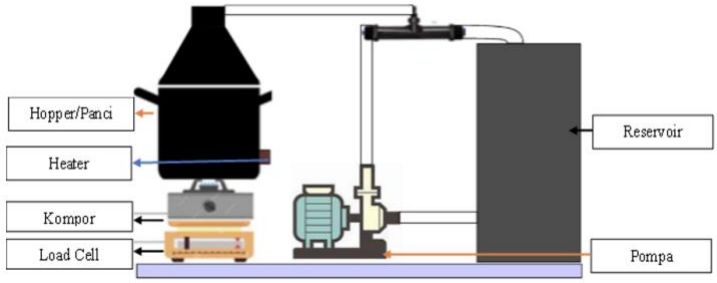


Figure 1. System design

The evaporation unit consists of a stainless-steel vacuum chamber equipped with induction heating (Wang *et al.*, 2025), thermal insulation system, type DS18B20 temperature sensor, digital vacuum manometer, and a load cell with a capacity of 100 kg for mass measurement. Thermal insulation is installed on the heating chamber and reservoir to minimize heat loss (Vondra, Máša and Bobák, 2018).

2.2. Materials and Test Conditions

The test was carried out using 40 kg of fresh palm sap. The evaporation process is carried out at a vacuum pressure of –0.71 to –0.73 bar and a liquid temperature of 34–41 °C. The temperature and pressure range is chosen to allow evaporation at low temperatures so that the quality of the sap is maintained and the risk of caramelization can be avoided. The duration of the process is consistently set for 150 minutes (2.5 hours).

The test was carried out once (single run) in sunny and stable weather conditions to allow optimal solar energy charging capacity. The limitation of the number of replications is listed as a limitation of the study.

2.3. Experimental Procedure

The phases of this experiment are as follows:

1). The solar panel is used to fully charge the battery before the process begins.
2). Palm sap is weighed using a load cell to obtain the initial mass of m_0.

3). Within 0 minutes, the vacuum pump and induction heater are activated simultaneously.
4). During the process, the data recorded every one minute includes mass, liquid temperature, reservoir temperature, vacuum pressure, as well as the electrical power consumption of the pump and heater.
5). After 150 minutes, the mass of battery or accumulator m_f was recorded, and Brix levels were measured using a digital refractometer.

The data obtained is then processed to calculate the evaporation rate and energy efficiency of the system (Wiyono, Erwin and Abdullah, 2021).

2.4. Evaporation Rate Calculation

The evaporation rate is calculated based on the change in mass over time using the equation (Sun *et al.*, 2023):

$$\dot{m}_{evap} = \frac{m_0 - m_f}{t} \quad (1)$$

where m_0 is initial Mass (kg); m_F is Final Mass (kg); and t is Time (hours). Using actual data m_0 = 40.00 (kg); m_F = 38.90 (kg); and t = 2.5 (hours), so the evaporation rate $\dot{m}_{evap} = 0{,}44\ kg/h$.

2.5. Energy Efficiency Calculation

The energy efficiency is calculated through a comparison between the latent energy of water evaporation and the electrical energy that enters during the process (Al-Obaidi *et al.*, 2025):

1). Calculation of useful energy.

$$E_{useful} = M_{evap} \times L \quad (2)$$

where M_{evap} is evaporative mass Kg/h and L is latent heat of water evaporation. Using actual data M_{evap}= 1.10 kg/h and L= 2257 kJ/kg at the working temperature range, so useful energy $E_{useful} = 2482.70\ kJ/kg$.

2). Calculation of incoming energy — full system (pump + heater).

$$E_{in} = P_{avg} \times t_s \quad (3)$$

where P_{avg} is expressed in kJ/s (conversion from W and t_s is time in second(s). Using actual data P_{avg}= 990 W = 0.990 kJ/s and t_s= 150×60 = 9000 s, so the incoming energy $E_{in} = 8910\ kJ$.

3). Heater-only efficiency.

$$\eta_{heater} = \frac{E_{useful}}{E_{in}} \times 100\% \quad (4)$$

where E_{useful} is energy useful for evaporation (kJ/kg) and E_{in} is electrical energy in the system (kJ). Using actual data E_{useful} = 2482.70 (kJ/kg) and E_{in}= 4635(kJ), so the heater-only efficiency $\eta_{heater} = 53.56\% \approx 53.6\%$.

2.6. Data Processing

Process data is recorded every one minute for 150 minutes, including sap mass, liquid temperature, reservoir temperature, vacuum pressure, and electrical power consumption. The raw data is checked first to ensure that there are no missing values or reading distortions (Chantasiriwan, 2020). Data processing is carried out in several steps. First, the initial and final masses are used to determine the evaporated mass of sap. This value is then calculated as the evaporation rate based on the difference in mass divided by the duration of the process. Next, the pump and heater power are taken from their average values to calculate the incoming electrical energy during the process by multiplying the average power and operating time. The latent energy is calculated using the evaporating mass and the latent heat of water evaporation.

In the test of a solar-powered vacuum evaporator, data on sap mass, operating temperature, vacuum pressure, and electrical power consumption are recorded periodically to assess the performance of the system. These parameters are the basis for calculating the amount of evaporated water as well as the energy efficiency of the process. Complete data on measurement results is presented in Table 1.

Table 1. Changes in mass and energy efficiency of the sap evaporation process in the vacuum evaporator system

No	Initial Mass (kg)	Final Mass (kg)	Evaporated Water (kg)	Operating Temperature (°C)	Pressure (bar)	Average Power (W)	Energy Efficiency (%)
1	40	39.8	0.2	34–36	–0.73	995	81.2
2	40	39.6	0.4	36–38	–0.73	992	82.5
3	40	39.4	0.6	37–39	–0.72	988	83
4	40	39.2	0.8	38–40	–0.72	986	84.1
5	40	38.9	1.1	40–41	–0.71	985	84.7

Table 1 presents the changes in sap mass during the evaporation process, operating temperature, vacuum pressure, average power consumption, and system energy efficiency. The initial mass and the final mass are used to determine the amount of water evaporated. Operating temperature indicates the temperature range of the liquid during the process, while pressure is a stable vacuum pressure maintained within the evaporation chamber (Erwin, Wiyono and Maulana Yusuf, 2024). The average power is calculated from the consumption of the induction heater and vacuum pump over the duration of the test. Energy efficiency is calculated as a ratio of evaporative latent energy to the total electrical energy entering the system. The increase in the amount of evaporated water shows an increasing trend in efficiency as the temperature and vacuum pressure stabilize in the operating range of 34–41 °C and –0.71 to –0.73 bar.

Figure 2 shows the complete configuration of the vacuum evaporator system used in this study. The system consists of an evaporation chamber, induction heater, vacuum pump, temperature sensor, pressure sensor, as well as a solar power array that includes solar panels, batteries, and inverters. The evaporation chamber is made of stainless steel to maintain hygiene and thermal stability. Induction heaters are installed at the bottom of the tank to ensure even heat distribution during the heating process.



Figure 2. Vacuum Evaporator

3. RESULTS AND DISCUSSION

3.1. Characteristics of Power Consumption During the Process

The performance of induction heaters and vacuum pumps can be observed from the power consumption patterns throughout the test. In the initial phase, the power is at a higher level as the system is still adjusting to operating conditions. The energy provided is not only used to heat the sap, but also to raise the temperature of the tank walls and metal components that have not yet reached thermal equilibrium. Once all components reach a state of tune, power consumption becomes more stable in the range of 985–995 W. This stability indicates that most of the incoming energy has been allocated to maintain the evaporation process under low pressure, no longer to raise the temperature of the system (Sarkar *et al.*, 2023).

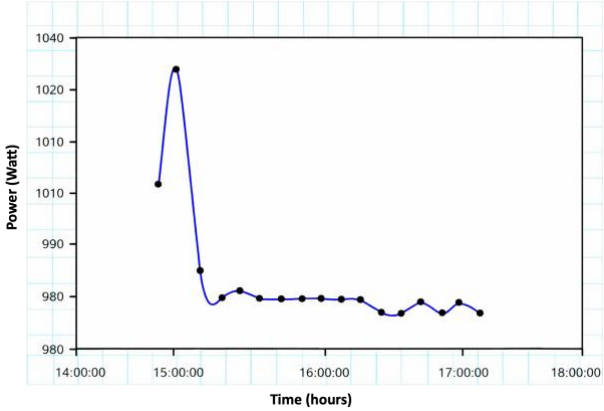


Figure 3. Total power

Figure 3 shows that the total power experienced a sharp increase at the beginning of the process, which is the system's response as the heater and pump work to reach the initial temperature of heating. After reaching its peak, the power immediately decreases and moves towards a stable state.

The examination of the graph's stabilization phase indicates a distinct pattern of damped oscillation culminating in equilibrium. After the abrupt decrease post-15:00, the system has a transitional decay period, during which peak values decrease from around 1005 at 15:22 to 998 at 15:55, and further

to 995 by 16:20. This indicates an initial decay rate of around 0.2 units per minute, which progressively diminishes as the system nears its steady state.

Between 16:00 and 17:45, the amplitude of the oscillations considerably constricts, with recorded values oscillating within a small range of 989 to 995. The computed mean for this conclusive stable phase is around 992 units. This signifies that the system effectively dissipated the energy from the first surge at 14:15, which peaked at 1035, ultimately stabilizing at a value around 4% below its highest. The steady convergence to this mean indicates a well-regulated operation that attains a dependable operating level after around two hours of fluctuation.

3.2. Evaporation Rate and Mass Dynamics

The change in mass showed that the evaporated water increased over time, with the total evaporation reaching 1.10 kg at the end of the process. The evaporation rate in vacuum conditions is influenced by the available energy as well as the magnitude of the vapor pressure gradient between the liquid surface and the vacuum chamber. At low pressures, water molecules more easily leave the surface of the liquid so that evaporation can run effectively even at relatively low temperatures. The evaporation rate value obtained is in line with the performance of other small-scale evaporators that utilize the vacuum principle (Ambarita, 2016).

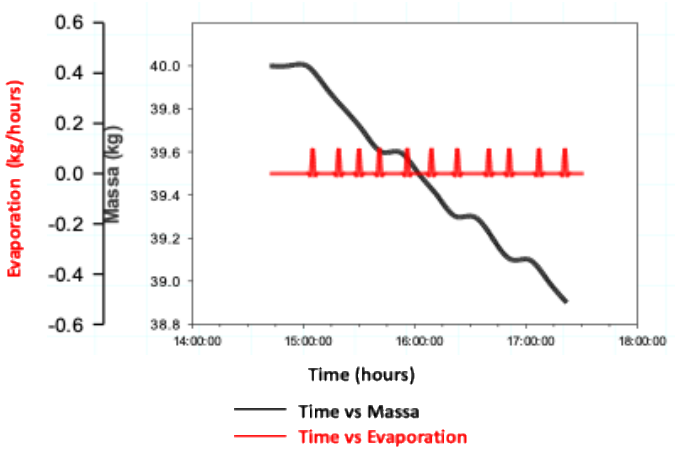


Figure 4. Mass graph under the influence of evaporation

Figure 4 shows the relationship between mass and temperature during the heating process. Mass line (black). From the chart pattern, this process is stable, characterized by a relatively constant decrease in mass with the average evaporation rate as seen in Figure 4 in red, about 0.1 kg/minute.

According to the graph's individual data points, the process starts at 16:00:15 with a starting mass of around 0.45 kg. From 16:00:25 to 16:00:30, the system experiences its highest intensity, as the red evaporation bars attain their greatest height, signifying a peak evaporation rate of around -0.12 kg/hour. In this "constant rate period," the black mass curve exhibits its most pronounced linear fall, decreasing swiftly as surface moisture is readily eliminated. As the timeline approaches 17:00:15, a discernible transition transpires: the mass curve starts to plateau, and the red bars diminish in height. This transition signifies the "falling rate period," during which the moisture within the material can no longer migrate to the surface rapidly enough to sustain the original velocity. At the conclusion of the collected data, the mass has decreased to about -0.18 kg, indicating a total relative loss of 0.63

kg from the initial value. The diminishing interval between the last data points indicates that the material is nearing an equilibrium moisture content, at which time the drying process inherently decelerates as it attains a stable dry condition.

3.3. Development of Vacuum Temperature and Pressure

The change in mass showed that the evaporated water increased over time, with the total evaporation reaching 1.10 kg at the end of the process. The evaporation rate in vacuum conditions is influenced by the available energy as well as the magnitude of the vapor pressure gradient between the liquid surface and the vacuum chamber. At low pressures, water molecules more easily leave the surface of the liquid so that evaporation can run effectively even at relatively low temperatures. The evaporation rate value obtained is in line with the performance of other small-scale evaporators that utilize the vacuum principle (Lourentius and Ayucitra, 2023).

A steady pattern of temperature rise on both curves indicates that the system is operating under conditions of constant heating, without any significant disruption to the energy supply. This ensures that thermal conditions support the evaporation process that is being analyzed in the study.

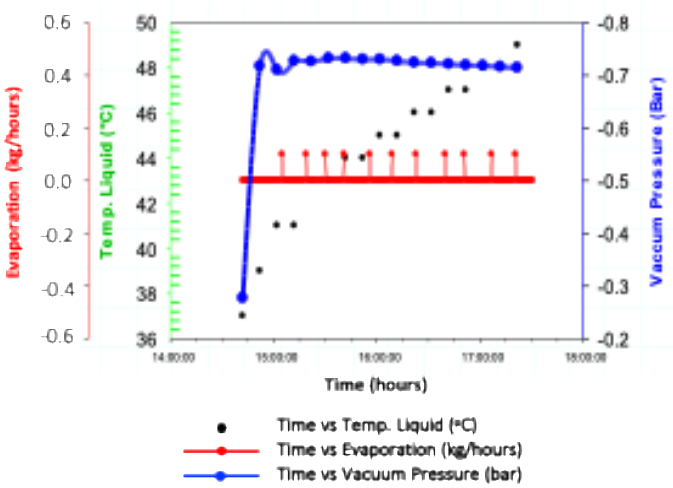


Figure 5. Dynamics of mass reduction and temperature

Figure 5 shows that the total power experienced a sharp increase at the beginning of the process, which is the system's response as the heater and pump work to reach the initial temperature of heating. After reaching its peak, the power immediately decreases and moves towards a stable state.

The provided graph illustrates a dynamic relationship between liquid temperature (green axis), vacuum pressure (blue axis), and resistance heater activity (red markers) over a four-hour window. A critical observation is the sharp initial spike in both vacuum pressure and temperature around 14:30, followed by a steady, synchronized decline. The vacuum pressure peaks near −0.75 bar and gradually relaxes toward −0.6 bar, while the temperature concurrently drops from approximately 49°C to 44°C. This correlation suggests a pressure-dependent cooling effect, where the increasing (less negative) vacuum pressure might be reducing the rate of evaporative cooling or indicating a system reaching thermal equilibrium. The resistance heater is depicted as a constant baseline with periodic fluctuations, suggesting it is being pulsed or modulated to maintain the liquid within a specific thermal range, likely to prevent the temperature from dropping too rapidly under vacuum.

The presence of black scatter points, which diverge slightly from the primary blue trend line after 16:30, may indicate minor measurement noise or secondary phase changes occurring as the system stabilizes. Overall, the data reveals a controlled cooling process where vacuum intensity and heat input are balanced to regulate the liquid's thermal state.

3.4. Energy Efficiency and Comparative Studies

The energy efficiency value is in the range of 81–85%, which can be categorized as high for vacuum-based electric heating systems. In comparison, conventional boiling processes at atmospheric pressure generally produce an efficiency of 25–40% due to high heat loss to the environment. In electric or other vacuum evaporators, the reported efficiency ranges from 70–85% depending on the quality of the insulation, the design of the heating chamber, and the stability of the operating conditions. Thus, the achievement of about 83% in this study shows that most of the energy provided has been utilized as latent energy for evaporation. Stable vacuum conditions, directed induction heating, and the use of thermal insulation contribute to this high ratio of useful energy (Ekka and Kumar, 2023).

3.5. Factors Affecting System Performance

Several technical factors play an important role in the performance of the system. First, thermal insulation reduces heat loss so that the energy requirement to maintain operating temperature is lower. Second, induction heaters generate a more even flow of heat at the bottom of the tank, which improves the efficiency of heat transfer to liquids. Third, operation at low temperatures and low pressures helps maintain the quality of the sap and suppresses the energy requirements to achieve the evaporation phase. The combination of these three factors explains the increased evaporation rate and efficiency achieved during the test.

4. CONCLUSION

This study reviewed the performance of solar-powered vacuum evaporators for the palm sap evaporation process in rural conditions without access to electricity. Using an induction heater and a vacuum system at a pressure of −0.71 to −0.73 bar, the evaporation process takes place at a low temperature of 34–41 °C. The measurement results showed that the corrected evaporation rate was in the range of 0.20–1.10 kg per test cycle, with stable power consumption in the range of 985–995 W and energy efficiency reaching 81–85%. These findings show that most of the energy supplied is successfully harnessed as latent energy evaporation.

Practically, the results of this study confirm that solar-based vacuum evaporators can be a viable solution for palm sap processing in rural areas or areas without electricity supply. This system offers an efficient, stable evaporation process and can maintain sap quality thanks to operation at low temperatures.

This research still has limitations, namely it is only carried out on one test condition and one tool capacity. Therefore, further research is needed to optimize the system design, evaluate performance at larger capacity, and conduct economic analysis to ensure the feasibility of implementation on a small industrial scale.

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