Solar Beeswax Melter

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Abstract: This research examines the potential of utilizing the solar energy to produce raw beeswax from old combs and capping wax byproducts. The solar beeswax melter comprises a stainless steel tank, a lean-to structure with polycarbonate sheet covers, an electric heater, and parallel rows of PV solar panels. Three different beeswax melting methods were used. The traditional water bath method, solar thermal energy method, and solar thermal energy combined with electric energy from solar panels. The efficiency of the melting process and the bulk temperature of the melted beeswax were measured during the conventional water bath method. For the solar wax melters, the melting process efficiency, bulk temperature of the melted wax, and various macroclimatic factors such as solar radiation, temperature, and relative humidity were recorded. Based on the experimental findings, the beeswax melting efficiency was determined to be 73.4%, 85.5% and 87.2% for the traditional water bath method, solar thermal energy method, and the combined solar method, respectively.

Keywords: capping wax byproducts, old combs, beeswax melter, melting efficiency, solar energy

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1 Introduction

Recently, there has been a notable surge in the exploration of sustainable and renewable energy options, driven by global efforts to address climate change and diminish carbon emissions. One promising avenue in this pursuit is the utilization of solar energy, tapping into the abundant and clean power of the sun to produce electricity. While solar panels are commonly associated with electricity generation, solar energy boasts diverse applications beyond residential and commercial electricity needs. One intriguing application involves using solar energy to liquefy beeswax, a versatile natural substance with numerous practical uses. By melting beeswax using solar power, we not only gain access to a replenishable resource but also promote environmental consciousness and contribute to the preservation of bee populations. Bees produce wax to construct their honeycombs, with fully developed wax glands typically becoming active around 12 to 18 days of age. Each bee possesses eight glands responsible for wax synthesis, and it takes about 3.629 kg of honey to produce 0.455 kg of beeswax. Beeswax holds not only intrinsic value but also the potential for significant revenue generation, as it is economically more valuable than honey on a per kilogram basis. Moreover, managing beeswax is simpler than honey, as it does not require delicate packaging and is not considered a food item, leading

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to easier transportation and storage (Bradbear, 2009). Moreover, beeswax has versatile uses, including the creation of polish, candles, and delicate wax sheets known as "foundation" sheets. Nowadays, a significant portion of produced wax is utilized in the cosmetics industry, including depilatory wax, hand and face creams, lipsticks, and various pharmaceutical products such as ointments, pills, and suppositories. According to Gemeda and Kebebe (2019), honey is three times more expensive per unit than beeswax on the global market. The Food and Agriculture Organization (FAO, 2022), predicts that global beeswax production reached 62,166 tons, with Asia, Africa, and America contributing 51%, 26%, and 22% respectively.

In Egypt, beeswax production in 2020 is 113 tons, with 61 tons imported, valued at 242 thousand dollars. Bees utilize beeswax, which has a creamy color, to build their nest combs. The color of pure beeswax can vary from white to yellow to yellow-brown depending on the proportion of pollen, propolis pigments, and other factors. There are two main techniques for extracting wax: chemical and melting (Sin et al., 2014). Additionally, old honeycombs can be utilized to obtain wax by removing small pieces of comb such as wax capping, frames, and hive components before extracting honey. The melting point of beeswax ranges from 62°C to 65°C, requiring a significant amount of energy for melting. Wax softens at 35°C and becomes malleable. Therefore, the wax needs to be melted out of the comb using sunlight, hot water, or steam to separate it from impurities before extraction, as explained by Mutsaers et al. (2005). Melter systems are designed and manufactured using electrical and solar heat supply technologies due to their simplicity. To prevent the wax from darkening, aluminum or stainless steel containers are suitable, ensuring that the wax does not directly contact the heat source, according to Bogdanov (2009). When heat energy is applied, beeswax absorbs it, causing the intermolecular bonds to break. According to Khamdaeng et al. (2016), the temperature range for the phase shift is between 18°C and 32°C, and the melting point begins within the range of 62°C to 65°C.

Furthermore, Egypt benefits from abundant sunlight. On average, Egypt receives 3050 hours of sunlight annually. The direct normal irradiation levels range from 1970 to 3200 kWh m^{-2}, while the annualized total solar irradiance ranges from 2000 to 3200 kWh m^{-2}, as reported by the solar atlas (Raslan and Ibrahim, 2024). As a result, Egypt's solar resources are remarkable and can be utilized in various solar energy systems and sectors. According to Moharram et al. (2022), this includes the potential for implementing photovoltaic (PV) or concentrated solar power (CSP) plant settings.

The microorganisms responsible for various bee diseases, such as European foul brood (EFB), American foul brood (AFB), and Nosema, can be present in old or damaged honeycombs. Solar energy stands out among renewable energy sources due to its non-polluting nature, cost-effectiveness, and abundant availability for a significant part of the year, along with manageable radiation intensity. Considering the limited number of studies on utilizing solar melters for beeswax processing in Egypt, this research aimed to identify an effective method for melting beeswax, to build and test a solar beewax melter**.**

2 Materials and methods

The experiments were conducted at the Faculty of Agriculture, Damietta University, which is geographically positioned at latitude 31.4224°N and longitude 31.6575°E. The study spanned from August 30 to September 12, 2022, with the objective of investigating the impact of solar energy on the melting process of raw beeswax. The wax melting occurred during daylight hours. Temperature readings were collected from 7:00 AM to 5:00 PM to document the temperatures inside and outside the experimental setup, as well as any detected fluctuations in these measurements.

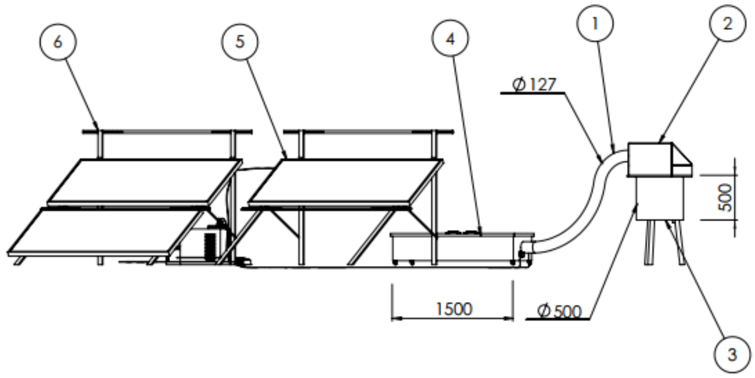
2.1 Materials

2.1.1 Sourcing Raw Beeswax

Dirty beeswax was obtained from aged brood frames, leftover from heather pressing, and the wax covering the cells. While cappings yield pure wax, the wax obtained from old brood combs is usually contaminated.

2.1.2 Solar Wax Melter Design and Function

The 2D drawing of the solar wax melter is shown in Figure 1 and photographed in Figure 2. A solar wax melter, is used to rapidly and effectively purify beeswax by raising the internal temperature of melting container to 68°C-70°C.



No.	Part name	No.off
1	Aluminum Pipe 5 in	1
2	Lean-to architectural Form	1
3	Stainless-steel Tank	1
4	Solar heater (Wooden heater)	1
5	Solar photovoltaic panels	3
6	Stand	2

Figure 1 2D of the solar wax melter

Figure 2 Photo of the solar wax melter

The tank, is made of stainless steel (No.3 in Figure 1), and it has a diameter of 50 cm and a depth of 59 cm. To minimize heat loss from the sides, the outer surface is thermally insulated. The prepared wax discs are placed on a perforated tray made of stainless steel with an area of 19.63 cm^2. The dimensions of the wooden framework for the lean-to architectural form (No. 2 in Figure 1) can be seen in Figure 3. Except for the back reflector, which is protected with nickel-chrome, the melter is covered with 2 mm polycarbonate panels to maximize the received amount of solar energy.

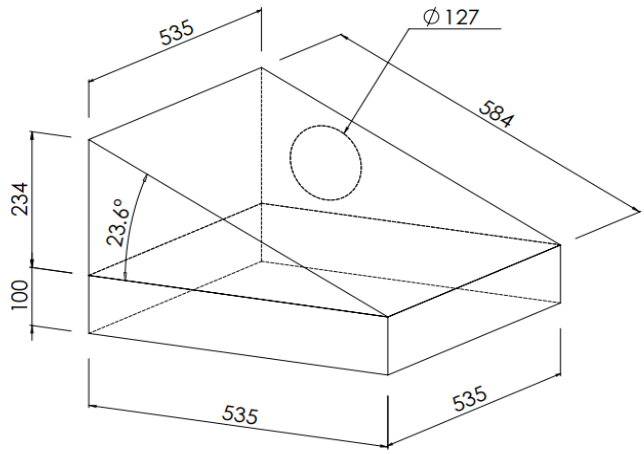


Figure 3 Sketched diagram for lean-to architectural form

To ensure safety and insulation, an electric heater (No.4 in Figure 1) was protected by a ceramic plate positioned underneath the thermal coil. The thermal coil was fastened to stainless steel screws and enclosed within a wooden box lined internally with fiberglass. This configuration prevents burns and provides efficient insulation for the solar heater. Three JSM-385M72 modules were utilized as solar photovoltaic panels (No. 5 in Figure 1). These panels were installed in parallel and placed at an optimal 30° angle with respect to the horizontal plane. They were securely mounted on a rectangular metal frame. The process of transferring heat to the melting container initiates with the solar panel's output energizing the thermal coil, effectively harnessing solar energy. The electric heater, indirectly powered by the solar panel, then activates, heating the thermal coil. Concurrently, a fan blows the heated air, further aiding in the transfer of heat. Consequently, the heat produced by the thermal coil, facilitated by the fan, is transmitted to the melting container.

2.2 Methods

The experiment had three distinct objectives. Firstly, it aimed to compare the traditional water bath method with the solar energy approach for melting beeswax. In the water bath method, an aluminum pan was filled with water and heated on a stove. A smaller aluminum pan containing 500 g of beeswax was then placed in the water bath and heated over medium heat until the wax melted.

In contrast, the solar-powered wax melter utilized the direct heat from the sun to melt the wax, eliminating the need for comb storage. This method was tested in two ways: firstly, by solely relying on solar energy, and secondly, by combining solar energy with additional heat from an electric heater powered by the solar PV. In the latter, hot air with an average speed of 0.8 m s^{-1} and a temperature of 60°C was used. The variations aim is to produce raw wax using the solar wax melter.

To achieve the lean-to architectural form while maximizing solar radiation intake, the ideal tilt angle of an inclined surface is determined using the equations established by Duffie and Beckman (2013). These equations provide guidance for calculating the optimal angle that ensures the highest amount of solar radiation is received.

$$\beta_o = \cos^{-1}[\cos(\phi)\cos(\delta)\cos(\omega)+\sin(\phi)\sin(\delta)] \tag{1}$$

$$\delta = 23.45\sin\left[(360)+\left(\frac{284+n}{365}\right)\right] \tag{2}$$

where: β_0 is the solar altitude angle in degrees, ϕ is the latitude angle (ϕ) for the study location (New Damietta) is 31.42°, ω is the solar hour angle and calculated as 15 (=*LAT*-12, *LAT* is local apparent time, δ is the solar declination angle and represents the position of the sun in relation to the celestial equator, and n is the number of days after January 1st.

2.2.1 Tested variables

All experimental parameters were measured as follows:

Primary measurements were conducted for the water bath method and comprised:

1) Bulk temperature of molten beeswax;

2) Melting process efficiency.

Secondary measurements were carried out for the solar wax melter and encompassed:

1) Beeswax melting period;

2) Ambient temperature;

3) Relative humidity;

4) Incident solar radiation;

5) Bulk temperature of molten beeswax;

6) Melting efficiency, calculated using the equation:

$$\text{EFF\%} = \frac{M_i - M_f}{M_i} \times 100 \tag{3}$$

where:

EFF% —melting efficiency (%);

M_i —initial mass (g);

M_f —the mass of remaining beeswax after melting (g).

7) The efficiency of the solar melter was determined using the equation:

$$\eta_c = \frac{P_{out}}{P_{in}} = \frac{(mC_p\Delta T + mL)}{P_{in}} = \frac{(mC_p\Delta T + mL)}{A_c I_b} \tag{4}$$

where:

η_c —efficiency of the system (%);

P_{out} —output power (W);

P_{in} —input power, m is the melting rate of wax (kg hr^{-1});

C_p—specific heat of beeswax (0.476 KJ kg^{-1} K^{-1});

$\Delta T= T_f-T_i$ (c°);

L — latent heat of fusion of the beeswax (242.8191 KJ kg^{-1});

A_c —collector area (m^2), I_b is the beam radiation (W m^{-2}).

2.2.2 Statistical analysis

The experiments were conducted in three separate runs. The experimental data was processed and all the graphs were generate using Microsoft Excel 2016, a software provided by Microsoft Corporation, based in Redmond, WA, USA.

3 Results and discussion

3.1 Water bath method

The results indicate that beeswax undergoes a phase transition from solid to liquid at an average temperature of 63.01°C, and it typically takes around 30.5 minutes for complete melting to occur (see Figure 4). These findings shed light on the kinetics of this phase change, offering practical implications. Regarding the water bath method's efficiency in melting beeswax, it ranged from 65.1% to 77.7%, with an average efficiency of 73.4%. This suggests that a significant portion of the applied heat effectively aids in wax melting. The variation in efficiency values underscores the impact of factors like heating rate, insulation, and container design on the overall efficiency of the process.

These results are consistent with previous studies by Krell (1996), Nuru (2007), and Bogdanov (2016), which also reported that the melting point of beeswax typically falls between 61°C and 66°C, ideally around 62°C to 65°C. The convergence of findings from multiple studies highlights the reliability and validity of the water bath technique for melting beeswax.

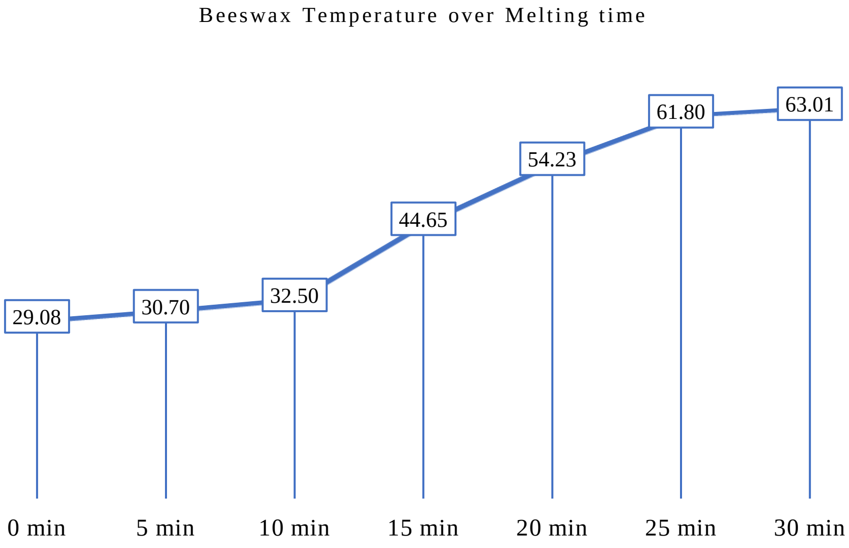


Figure 4 Beeswax temperature during melting using a water bath

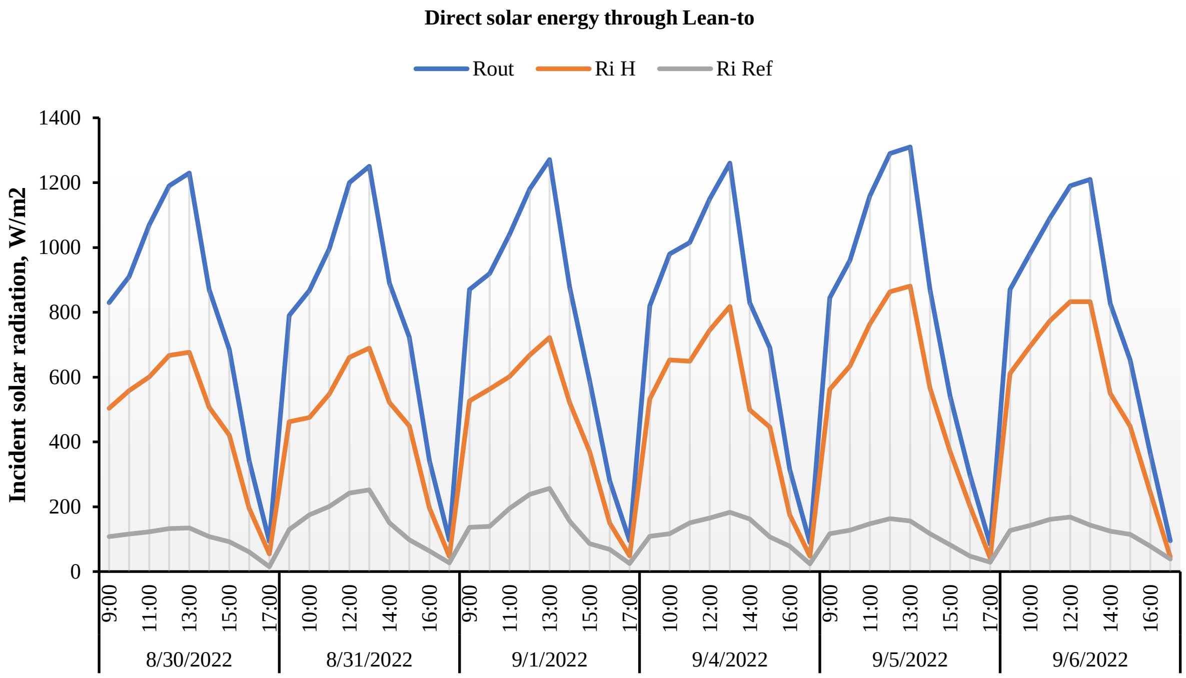
3.2 Solar wax melter

In the initial setup, the wax melting process ranged from 150 to 360 minutes, with an average duration of 243.3 minutes. In contrast, the second setup required 90 to 240 minutes, averaging at 183.3 minutes. These findings highlight a significant reduction in melting time achieved through the utilization of solar energy compared to the traditional water bath technique, which typically takes about 30.5 minutes. Additionally, an evaluation of melting efficiency for the solar wax melter was conducted. In the first configuration, melting efficiency ranged from 66.9% to 95.1%, with an average efficiency of 85.5%. Similarly, the second setup showed melting efficiency ranging from 81.4% to 92.1%, with an average efficiency of 87.2%. These results underscore the superiority of the solar wax melter over the conventional water bath method in terms of melting efficiency. The use of solar-electric heater in the second setup enhanced the melting efficiency and reduced melting time. By maintaining an average temperature of 60°C and an average airflow velocity of 0.8 m s^{-1}, the solar heater facilitated the heat transfer process, resulting in quicker and more effective melting of the beeswax.

3.2.1 Incident solar radiation flux

The incident solar radiation on the wax melter, was measured inside and on the surface of the melting box. Over the initial six days of practical experimentation, the incident solar radiation within the melter ranged from 70 to 1037 W m^{-2}, and from 84 to 1310 W m^{-2} outside the melter. These measurements highlight the significant variability in solar energy availability and emphasize the need to account for radiation fluctuations to optimize the melting process. The average hourly solar radiation accessible within the collector was 622.15 W m^{-2}, while external measurements showed 801.55 W m^{-2}. These values offer insights into the typical solar energy levels suitable for beeswax melting. It's important to note that these figures are specific to this study and may vary based on geographic location and time of year. In the second configuration, measurements within the melter ranged from 50 to 1014 W m^{-2}, with exterior readings ranging between 67 and 1190 W m^{-2}. The average hourly solar radiation measured outside and inside the melter were 776.60 W m^{-2} and 607.3 W m^{-2}, respectively. These values underscore the inherent variability in solar radiation and stress the importance of optimizing the approach to effectively capture and utilize energy. Fluctuations in incident solar radiation measured externally, within the collector, and reflected from the vertical back wall throughout the experimental phase are depicted in Figure 5.

This graphical representation show the dynamic nature of solar energy and the challenges associated with maintaining consistent heat input during the beeswax melting process. The results highlight the importance of vigilant monitoring and control of the solar energy system to accommodate variations in incident radiation. Approaches such as efficient solar collector design, tracking mechanisms, and thermal storage systems can help mitigate the impact of fluctuating solar radiation and ensure a more stable heat source for melting beeswax.



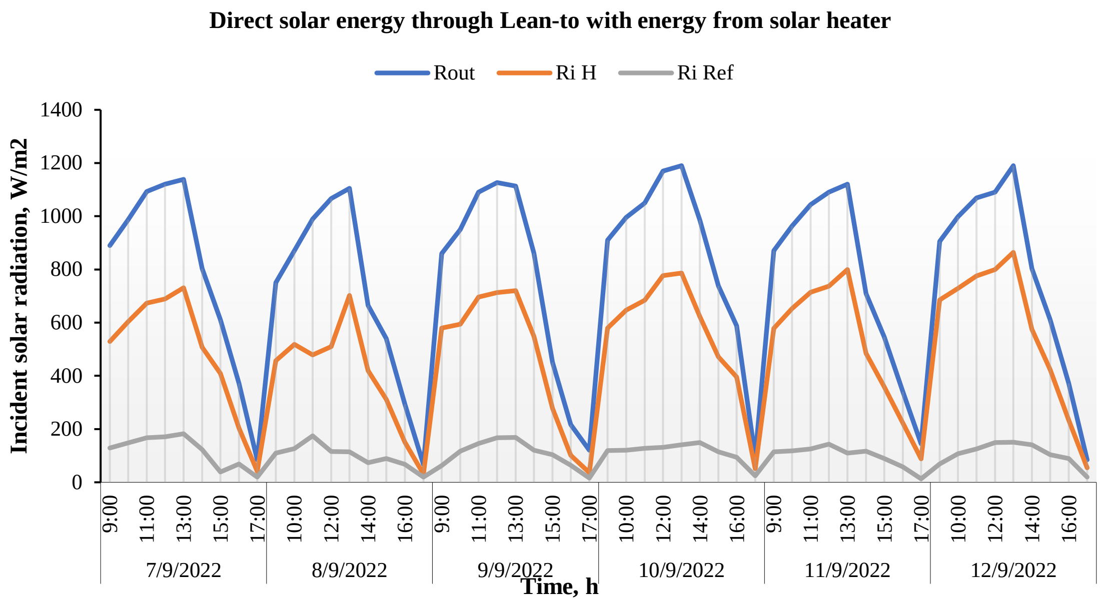
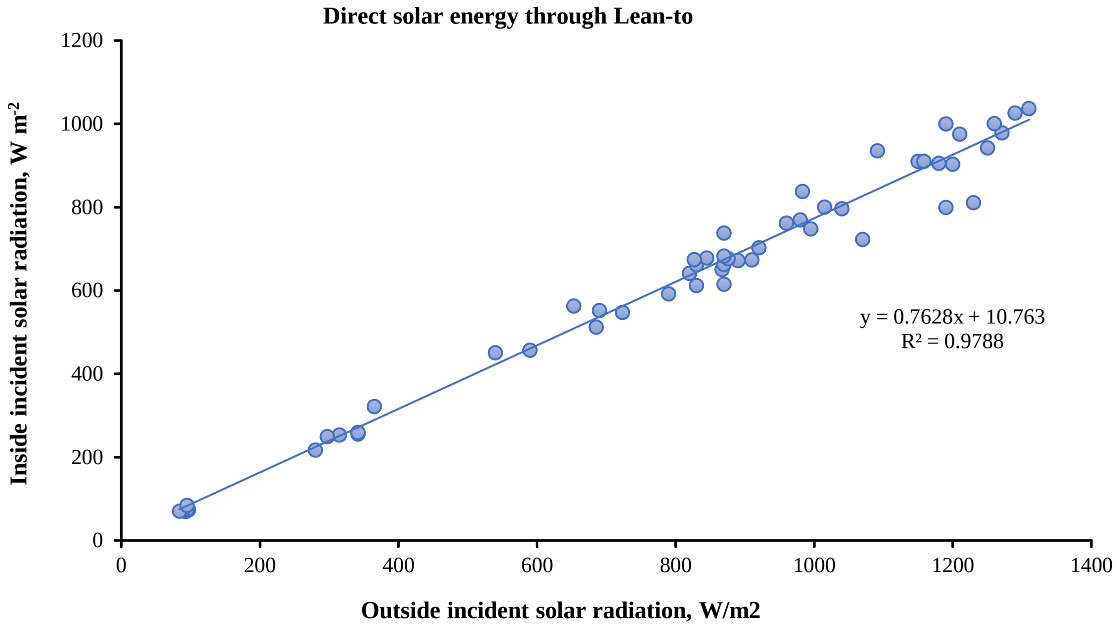


Figure 5 Depicts the daily fluctuations in incoming solar radiation, both within and outside the collector, along with the reflected radiation from the vertical-back wall during the experimental period for the two systems

Figure 6 illustrates a visual representation of the relationship between the solar radiation entering the collector and the solar radiation measured externally. This connection provides valuable insights into the efficiency of the transparent polycarbonate cover in facilitating solar radiation entry into the collector. Analyzing the correlation between solar radiation entering the collector and external measurements is crucial for understanding the effectiveness of harnessing solar energy. This examination can offer valuable information about the polycarbonate cover's ability to transmit and capture solar energy efficiently for the wax melting process. Moreover, examining the correlation between solar radiation levels within and outside the collector can help identify potential losses or inefficiencies in the system. Discrepancies in solar radiation values may indicate factors such as reflection, absorption, or dispersion of solar energy within the collector. Through careful adjustment of the transparent polycarbonate cover's design, researchers and engineers can strive to maximize solar energy capture and minimize losses, thereby enhancing the overall efficiency of the beeswax melting process. The results presented in this study stem from a straightforward power regression analysis conducted to establish the relationship between changes in incident solar radiation within a solar collector and incident solar radiation outside. Two distinct systems were investigated, each yielding its unique regression equation. For the first system, where direct solar energy is captured through a lean-to structure, the regression equation is as follows: $y = 0.7628x + 10.763$ (R^2 = 0.9788). This equation indicates that the incident solar radiation inside the lean-to structure (y) is influenced by the incident solar radiation outside (x) according to this mathematical relationship. The high coefficient of determination (R^2 = 0.9788) suggests that this equation effectively explains and predicts changes in solar radiation within the collector based on external conditions. The strong correlation implies that this system robustly responds to variations in solar radiation.

Moving on to the second system, which involves direct solar energy through a lean-to with additional energy from a solar heater, the regression equation is: $y = 0.7838x + 1.5014$ (R^2= 0.9724). Again, we observe a positive relationship between incident solar radiation inside and outside, albeit with a slightly different equation due to the influence of the solar heater. In this case, the R^2 value of 0.9724 still indicates a strong correlation, suggesting that the introduction of the solar heater does not significantly weaken the predictive power of the model. This result indicates that the system's performance remains robust and can be effectively characterized by this equation. In both cases, it's important to note that '*y*' represents the incident solar radiation inside the collector, while '*x*' represents the incident solar radiation outside.

These regression equations and associated R^2 values provide valuable insights into the behavior of these solar energy collection systems, aiding in their optimization and potential application in various contexts, such as renewable energy production and sustainable heating solutions. Further research and experimentation can build upon these findings to enhance the efficiency and effectiveness of such systems.



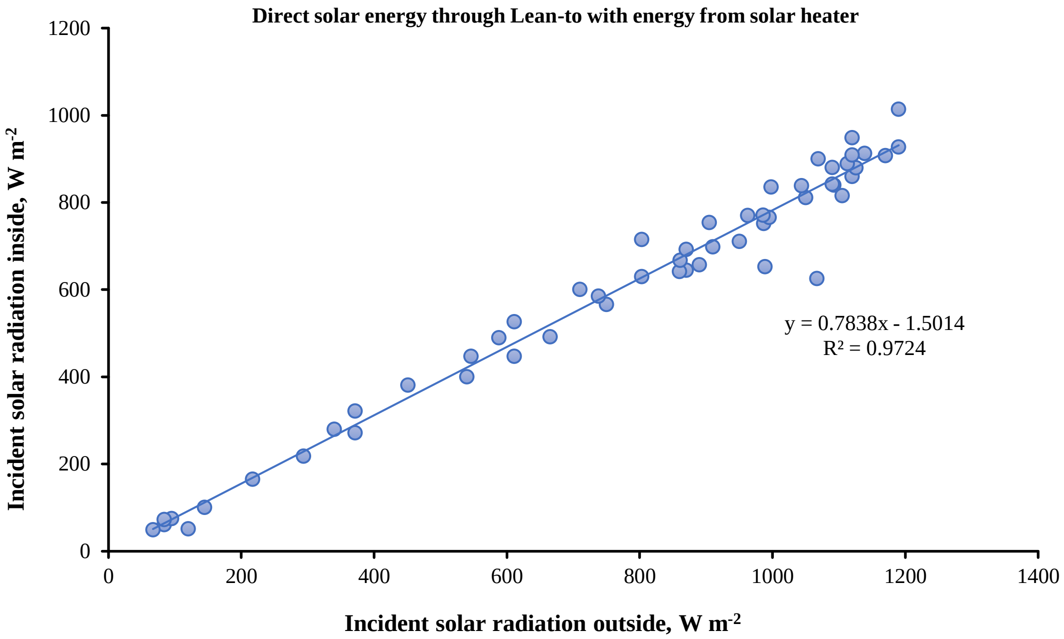


Figure 6 Illustrates the correlation between the incident solar radiation within the solar collector and the incident solar radiation outside for both systems

3.2.2 Ambient temperature and relative humidity

The results highlight the importance of temperature and humidity in facilitating the phase transition of a substance from solid to liquid. The melting process involves increasing the internal energy of a solid, typically through the application of heat, allowing it to reach its melting point and undergo fusion (Sofekun et al., 2018). In the case of beeswax, heat application is essential for transitioning it to a molten state, requiring the addition of latent heat, specifically the heat of fusion. Throughout the experiment, researchers documented the average hourly ambient temperatures outside and inside a lean-to solar collector for two distinct systems. For the initial system, the average outdoor and indoor ambient temperatures were recorded as 29.85°C and 46.91°C, respectively. Similarly, for the second system, the corresponding values were 29.84°C outdoors and 46.25°C indoors. These measurements offer insights into the temperature conditions surrounding the wax melter during the experimentation. The results also indicate the percentage increase in ambient temperature for each system. The first system demonstrated a 57.14% increase in ambient temperature, while the second exhibited a 55% rise.

These findings demonstrate the effectiveness of the lean-to solar collector technique in significantly raising the indoor ambient temperature within the wax melter. Furthermore, researchers observed a notable impact of indoor ambient temperature on the overall temperature of the beeswax when employing the lean-to solar collector technique under specific experimental conditions. It is conceivable that Figures 7 and 8 visually represent this correlation, illustrating the connection between indoor ambient temperature and beeswax temperature. Data analysis supported these observations, confirming the link between indoor ambient temperature and beeswax melting temperature. These findings emphasize the crucial role of ambient temperature in the beeswax melting process. Higher indoor ambient temperatures within the wax melter facilitate more efficient heat transfer and subsequent beeswax melting. The lean-to solar collector technique, which harnesses solar energy and promotes elevated indoor ambient temperature, provides a means for achieving effective beeswax melting.

In the initial system, the average indoor relative humidity within the solar collector was 36.1%, contrasting with an external humidity of 68.71%. Likewise, for the second system, these respective values were 38.28% and 71.24%. These measurements underscore the disparity in humidity levels between the interior and exterior of the wax melter during the experiment. The solar extractor, a vital component of the solar collector system, played a crucial role in reducing indoor relative humidity. In the first system, the solar extractor effectively decreased indoor relative humidity within the solar collector by approximately 32.61%. Similarly, in the second system, it lowered indoor relative humidity by around 32.96%. These findings underscore the significant contribution of the solar extractor in maintaining lower indoor relative humidity levels within the wax melter. These findings stem from a power regression analysis investigating the correlation between the change in bulk temperature of beeswax and the indoor ambient temperature within a lean-to solar collector for two distinct systems: one operating solely on direct solar energy and another supplemented with energy from a solar heater. The resulting regression equations for these systems are as follows: For direct solar energy through lean-to (without additional energy input):

$y = 1.1085x - 3.0082$ ($R^2 = 0.7423$).

For direct solar energy through Lean-to with energy from a solar heater (with additional energy input): $y = 1.1445x - 2.772$ ($R^2 = 0.6279$). These equations articulate the mathematical relationship between the bulk temperature (y) of the beeswax and the indoor ambient temperature (x) within the lean-to solar collector for the two systems. They offer a predictive tool to estimate the bulk temperature based on the indoor ambient temperature for each system. The R^2 value serves as an indicator of the regression equation's alignment with the data points, representing the proportion of variance in bulk temperature attributable to changes in the indoor ambient temperature. Both equations are accompanied by R^2 values to assess the goodness of fit. A higher R^2 value indicates a better fit for the data. Notably, the system operating solely on direct solar energy through Lean-to exhibits a slightly higher R^2

value (0.7423) compared to the system with energy input from a solar heater (0.6279). This suggests that changes in the indoor ambient temperature have a more significant influence on the bulk temperature of beeswax in the first system. These findings hold practical significance in the field of solar energy collection and utilization, providing insights into how the bulk temperature of beeswax, often employed as a heat storage medium, reacts to changes in indoor ambient temperature within Lean-to solar collector systems.

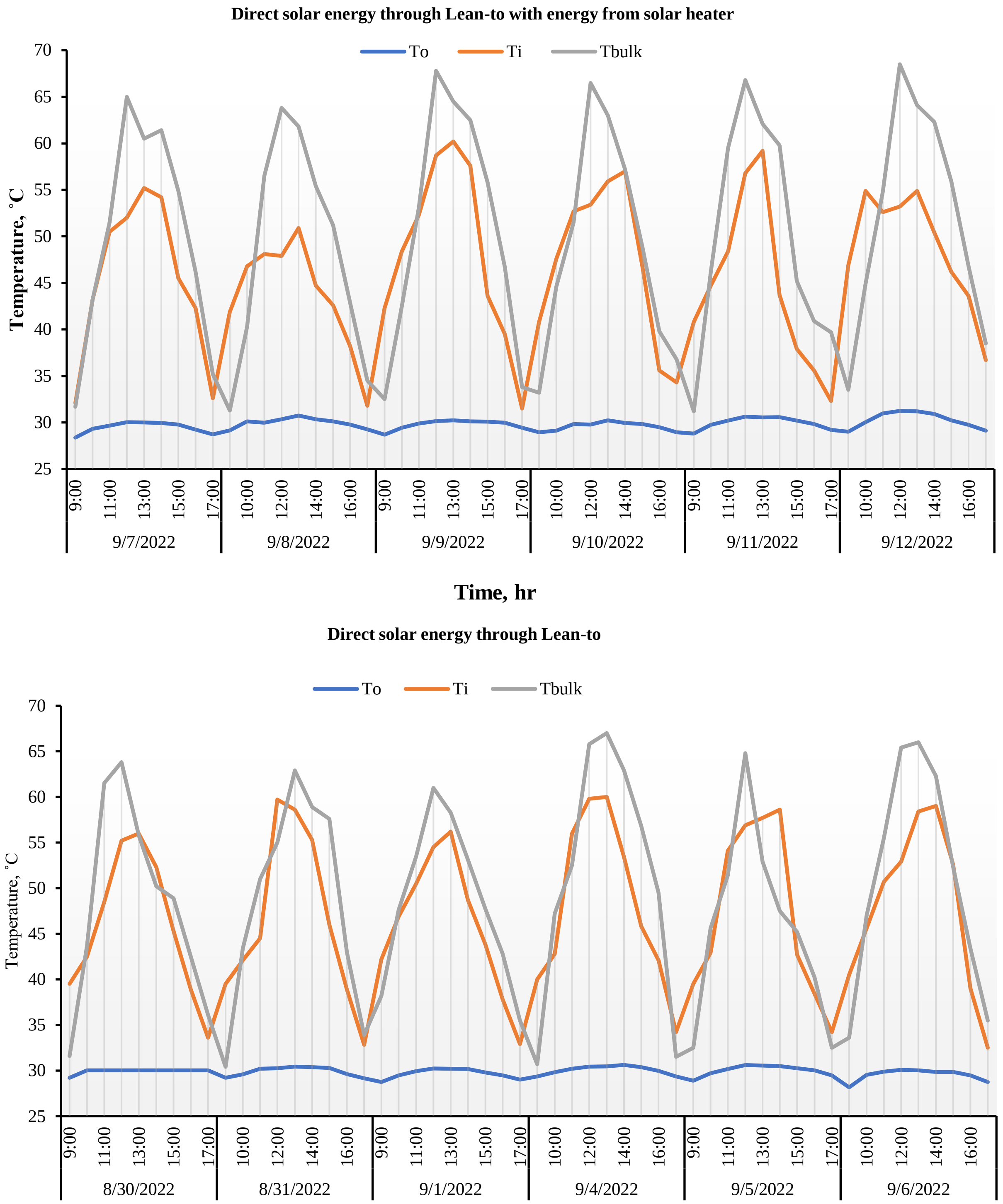
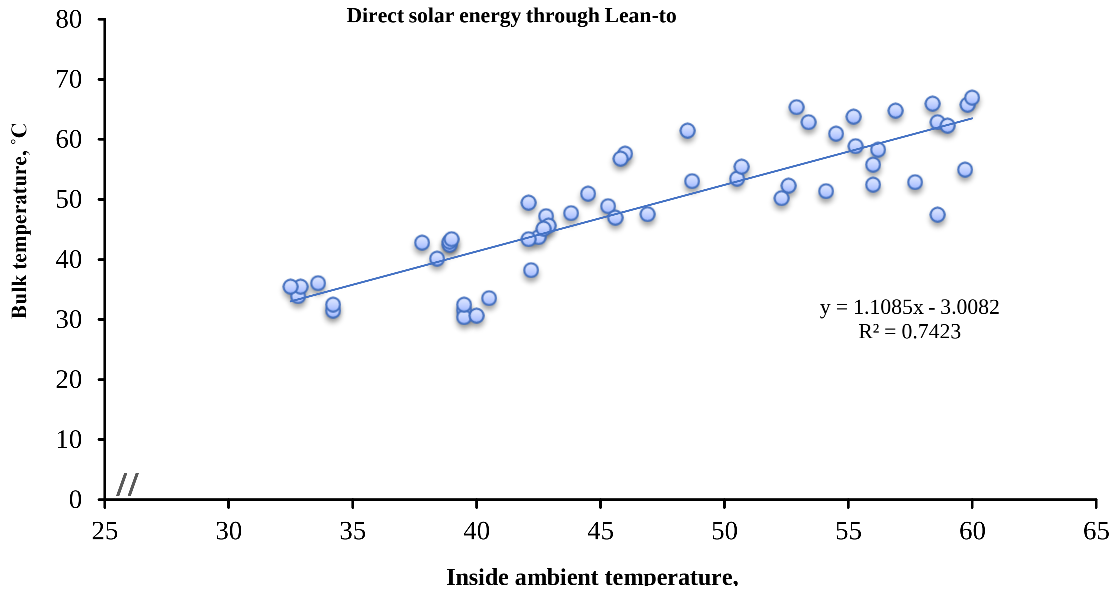


Figure 7 Illustrates the daily fluctuations in bulk and ambient temperatures, both inside and outside the solar collector, over the course of the experiment for the two distinct systems



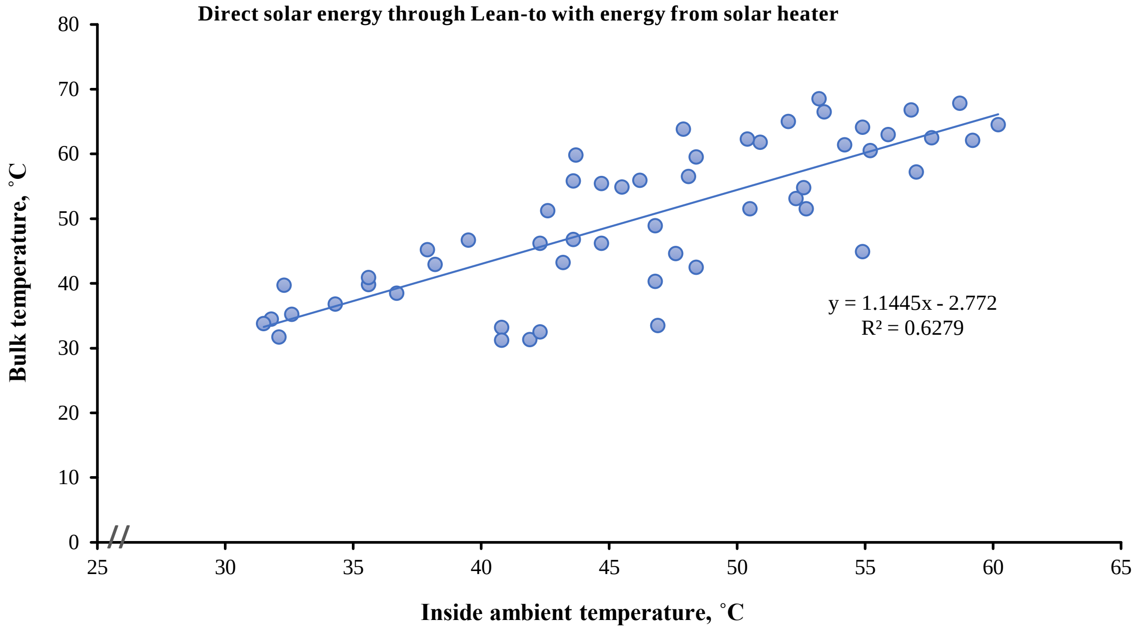


Figure 8 Displays the correlation between the bulk temperature of beeswax and the indoor ambient temperature within the lean-to solar collector for both of the investigated systems

Engineers and researchers can utilize this knowledge to enhance the performance of such collectors under varying energy input conditions. In conclusion, the regression results offer valuable insights into the relationship between bulk temperature and indoor ambient temperature in Lean-to solar collector systems, laying the groundwork for further research and optimization efforts in solar energy collection and utilization. Figure 9 visually illustrates the fluctuations in indoor and outdoor relative humidity levels within the solar collector, offering a clear understanding of the divergence in humidity conditions and the effectiveness of the solar extractor in reducing indoor relative humidity. The impact of relative humidity on the beeswax melting process is noteworthy. Elevated humidity levels can affect heat transfer efficiency and increase moisture content in the beeswax, potentially altering its properties. Therefore, reducing indoor relative humidity within the wax melter is essential for maintaining optimal conditions for effective and consistent beeswax melting.

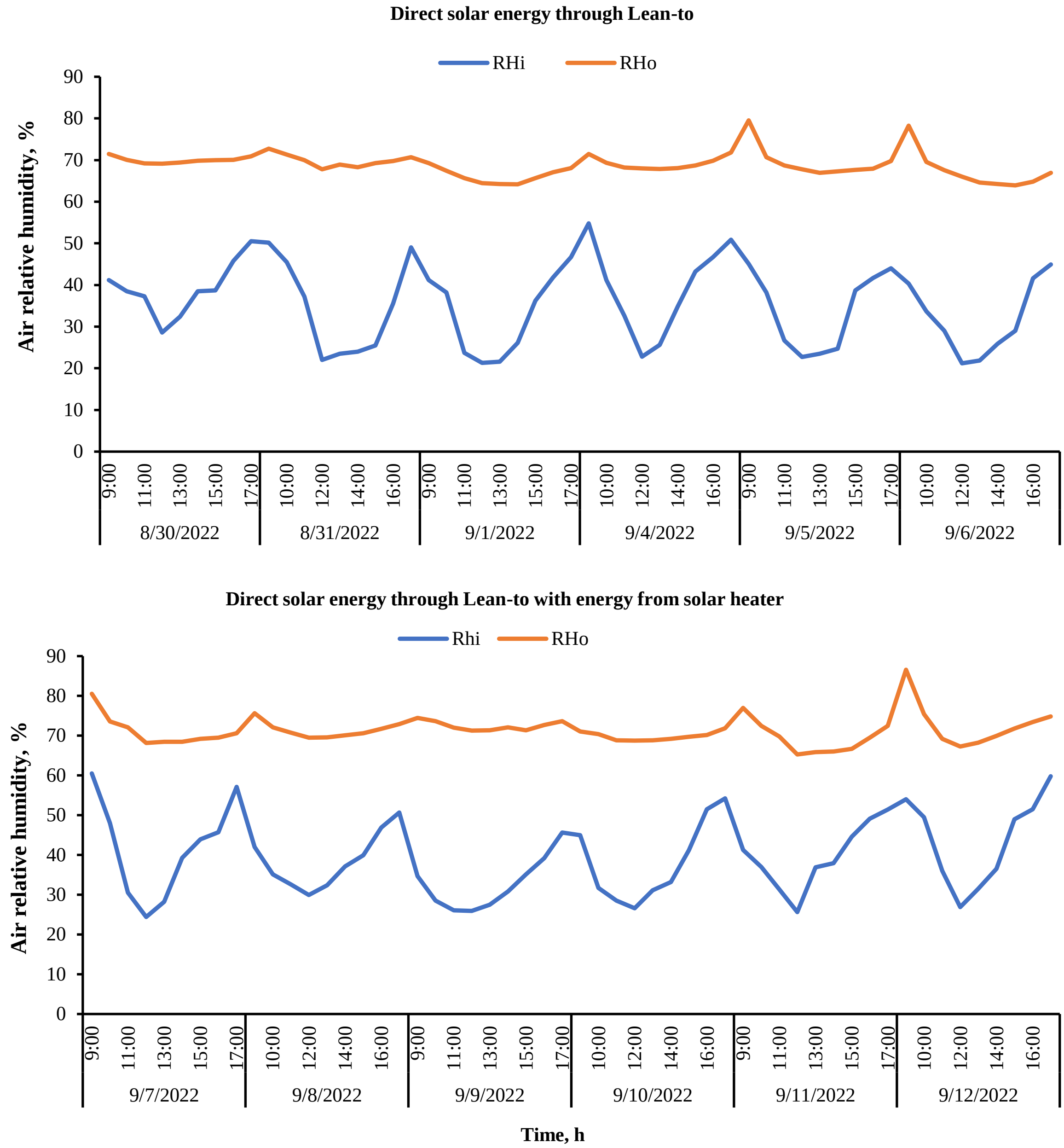


Figure 9 The daily variations in relative humidity levels both inside and outside the solar collector were monitored throughout the experimental period for the two systems

The study reveals a significant relationship between air temperature and relative humidity, particularly during daylight hours, where changes in air temperature affect the air's moisture-holding capacity. It highlights the solar collector's ability to lower indoor relative humidity compared to outdoor levels while simultaneously raising indoor temperatures above outdoor levels. This environment results in indoor air becoming both drier and warmer than external conditions. This reduction in indoor relative humidity within the solar collector, attributed to features like the solar extractor, creates less favorable conditions for moisture retention, benefiting beeswax melting by preventing excessive moisture absorption and preserving its characteristics. Additionally, the higher indoor temperature expedites the melting process, facilitating efficient heat transfer and ensuring the rapid attainment of the beeswax's melting point. Furthermore, the warmer and drier atmosphere within the solar collector effectively absorbs and removes moisture released during melting, preventing moisture accumulation and maintaining the desired consistency and characteristics of the melted wax. Overall, these findings underscore the advantages of utilizing a solar collector for beeswax melting, including faster melting times and reduced moisture-related issues.

3.3 Efficacy of the system

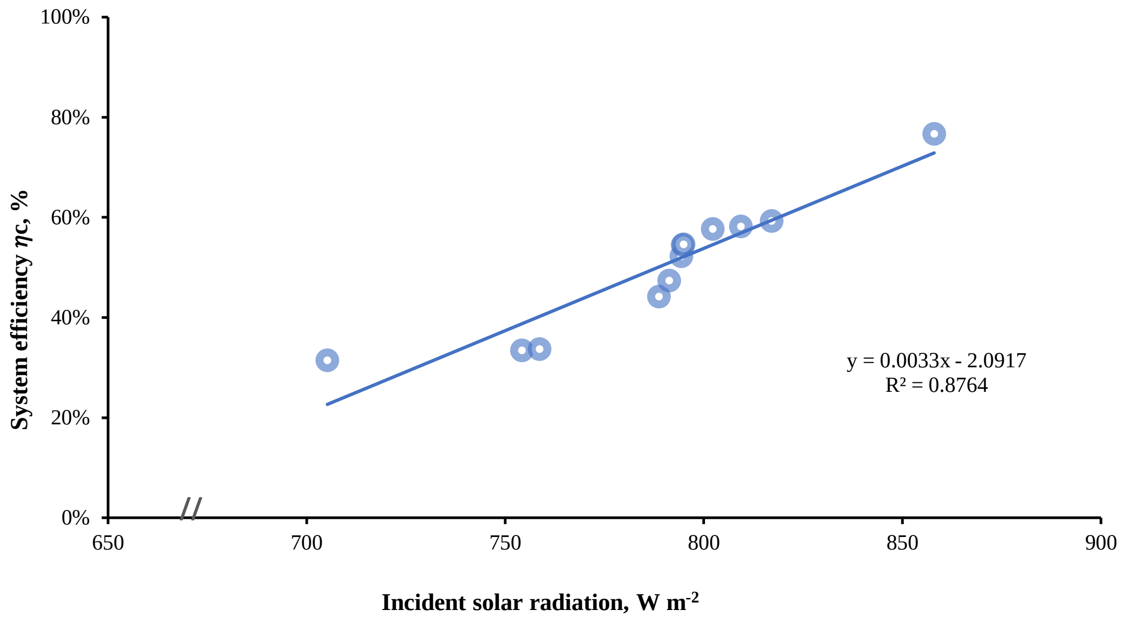
The study outcomes provide insights into the efficiency of two different systems employed for beeswax melting. The initial system demonstrated efficiency ranging from 31.4% to 61.6%, with an average of 44.1%. Conversely, the second system exhibited a wider range of efficiency values, spanning from 44.1% to 76.6%, with an average efficiency of 59.2%. These efficiency measurements indicate how effectively each system converts solar energy into heat for the melting process. The second system, on average, showed superior efficiency compared to the initial system, suggesting that it utilized available solar energy more effectively. It's worth noting that the macroclimatic conditions surrounding the solar collector significantly influence the efficiency of the wax melting systems. Factors such as incident solar radiation, ambient temperature, and relative humidity play crucial roles in determining the overall efficiency of these systems.

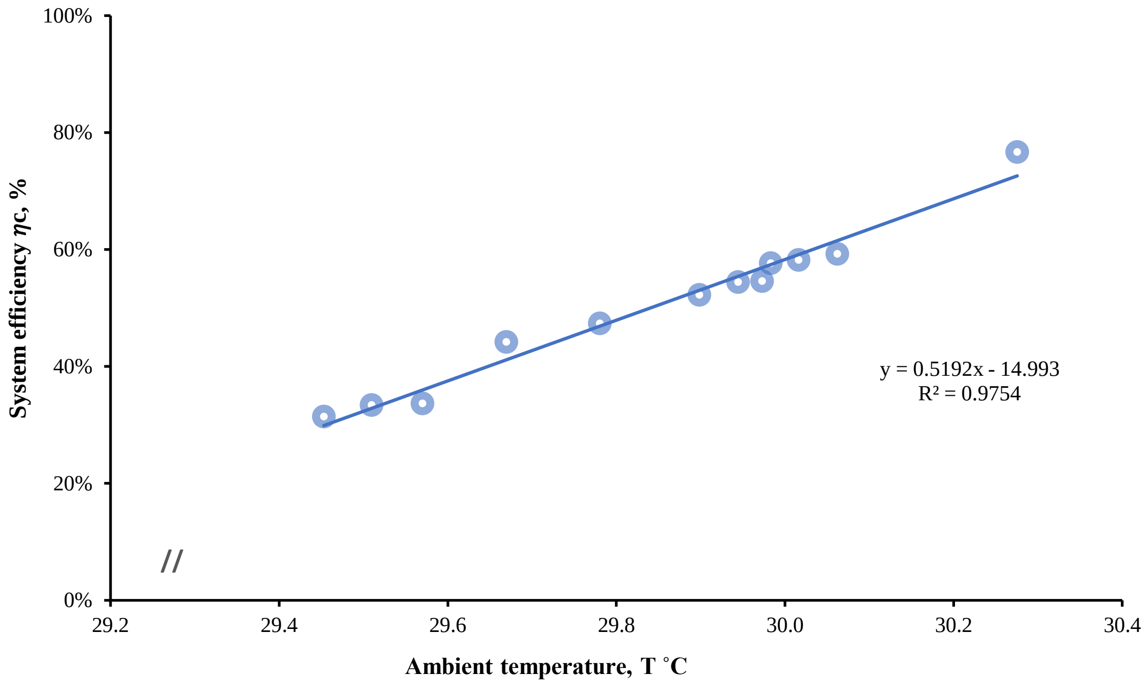
Figure 10 presents a graphical representation of the relationship between system efficiency and the aforementioned factors. This visualization helps in understanding how fluctuations in incident solar radiation, ambient temperature, and relative humidity affect the efficiency of the wax melting systems. The correlation between system efficiency and incident solar radiation is crucial, given that solar energy serves as the primary heat source for these systems. Higher levels of incident solar radiation typically result in increased energy input, leading to higher system efficiency. Furthermore, the relationship between system efficiency and ambient temperature underscores the importance of maintaining optimal temperature conditions for effective wax melting. Elevated ambient temperatures create favorable conditions for heat transfer, resulting in reduced melting time and improved system efficiency.

Similarly, the association between system efficiency and relative humidity emphasizes how moisture content in the surrounding air affects the wax melting process. Lower relative humidity levels create a drier atmosphere, preventing excessive moisture absorption by the beeswax and preserving its characteristics, ultimately contributing to higher system efficiency. Understanding these correlations helps identify key factors influencing system efficiency and informs the optimization of wax melting systems. By considering the effects of incident solar radiation, ambient temperature, and relative humidity, researchers and engineers can develop strategies to maximize system efficiency under varying macroclimatic conditions.

The findings of this study align with research conducted by Khan et al. (2019), who investigated the relationship between daily candle production and variations in average solar radiation measured in W/m^2. Khan et al. utilized solar energy to heat and liquefy beeswax, a process similar to the one examined in the current study. The results of Khan et al. (2019) indicated a direct correlation between solar radiation intensity and the effectiveness of the melting process, suggesting that higher solar radiation levels result in more efficient wax melting. These findings are consistent with the outcomes of the present study, which establish a connection between system efficiency and incident solar radiation. Furthermore, Khan et al. (2019) also identified a relationship between ambient temperature and the efficiency of the melting process. The findings of the present study, which demonstrate the impact of ambient temperature on beeswax melting, are in line with this earlier research. These consistent findings across studies provide significant evidence that solar radiation and ambient temperature play crucial roles in the wax melting process. Leveraging higher solar radiation levels and maintaining elevated ambient temperatures contribute to more efficient and effective melting of beeswax.

The convergence of these results underscores the importance of considering solar radiation and temperature factors in the design and optimization of wax melting systems. Maximizing the utilization of solar radiation potential and ensuring suitable ambient temperature conditions can greatly enhance the efficiency and productivity of candle production and other applications dependent on melted beeswax. The primary aim of this study was to conduct a quantitative analysis to establish the relationships between system efficiency and key environmental parameters. Understanding these relationships is crucial for optimizing energy systems and adapting them to varying environmental conditions. For the relationship between system efficiency and incident solar radiation, the regression equation is $y= 0.0033x - 2.0917$, with an R^2 of 0.8764. Regarding system efficiency versus ambient temperature, the equation is $y= 0.5192x - 14.993$, and the R^2 is 0.9754. Finally, for system efficiency versus air relative humidity, the equation is $y= 0.0617x - 3.8151$, with an R^2 of 0.8249. The linear form of these equations suggests a direct and proportional relationship between system efficiency and each environmental variable.





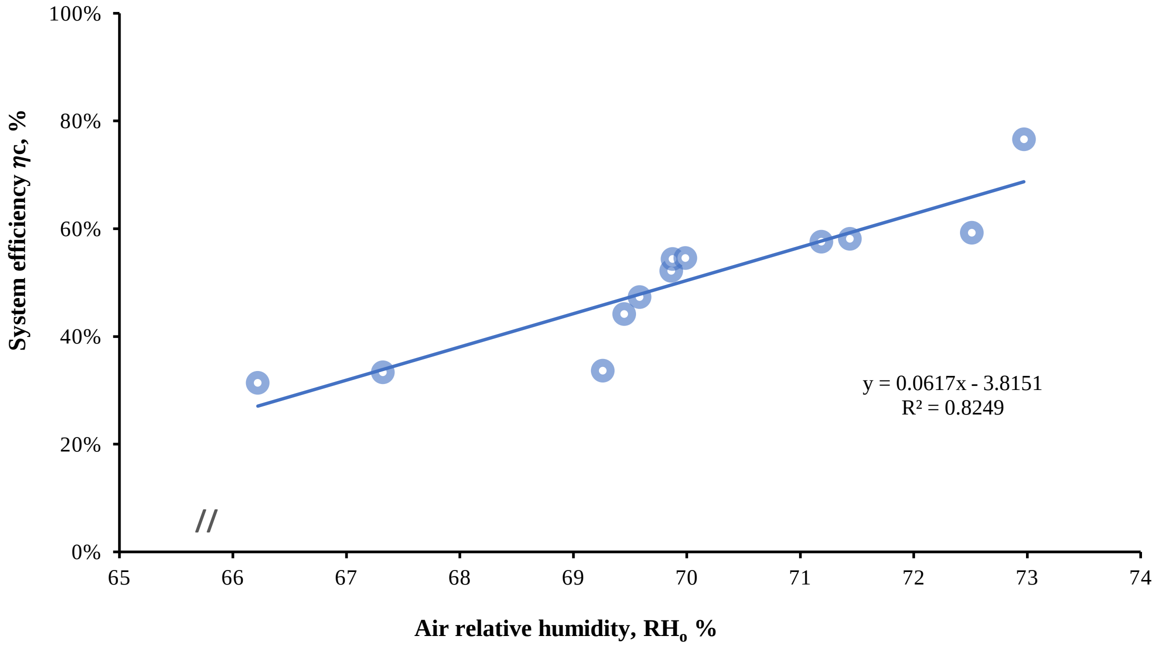


Figure 10 Depicts the direct correlation between system efficiency and incident solar radiation, ambient temperature, and relative humidity

By calculating the R^2 values, we assessed how well these regression models fit the data, representing the proportion of variance in system efficiency explained by changes in the respective environmental variable. The correlation between system efficiency and incident solar radiation is positive but moderately weak (R^2= 0.8764), indicating that while solar radiation impacts efficiency, other factors may also contribute to variations in system performance. Conversely, system efficiency and ambient temperature exhibit a very strong positive correlation (R^2= 0.9754), emphasizing that ambient temperature significantly influences system efficiency, with higher temperatures associated with increased efficiency. Although there is a positive correlation between system efficiency and air relative humidity, it is slightly weaker compared to temperature (R^2= 0.8249), suggesting that humidity plays a role but to a lesser extent than temperature. These results are valuable for engineers and energy system designers, providing them with regression equations to optimize energy systems while considering the impacts of incident solar radiation, temperature, and humidity on efficiency. Additionally, the robust correlation between system efficiency and ambient temperature underscores the importance of implementing climate adaptation measures to maintain optimal efficiency under varying temperature conditions. Furthermore, these relationships can inform energy forecasting and system planning, enabling more accurate predictions of energy production and consumption for efficient energy management.

4 Conclusion and recommendations

This study compared two distinct beeswax melting methods: the conventional water bath approach and a solar-powered wax melter. The water bath method exhibited an average efficiency of 73.4% and melted the beeswax in approximately 30.5 minutes on average. In contrast, the solar-powered wax melter demonstrated higher efficiency, averaging 85.5% and 87.2% for the two examined systems. Despite longer melting times ranging from 90 to 30.5 minutes, the solar-powered method proved superior to the traditional approach. The performance of the solar-powered wax melter was significantly influenced by the incident solar radiation flux. However, reliance on solar energy necessitates careful control due to fluctuations caused by factors like clouds, fog, and time of day. The experiment documented variations in incident solar radiation both inside and outside the solar collector, ranging from 70 to 1037 W m^{-2} and 84 to 1310 W m^{-2}, respectively. Similar fluctuations were observed in the second system, with readings ranging from 50 to 1014 W m^{-2} inside and 67 to 1190 W m^{-2} outside. The transparent polycarbonate covering of the solar collector played a crucial role in regulating the amount of solar radiation entering the collector. Ambient temperature and relative humidity exerted notable effects on the melting process. The average hourly ambient temperatures outside and inside the solar collector measured approximately 29.8°C and 46.9°C for the first system, and 29.8°C and 46.3°C, respectively, for the second system. The solar collector raised indoor temperatures above outdoor levels, resulting in shorter melting durations. Relative humidity inside the solar collector decreased by approximately 32.6% to 32.96% compared to outdoor levels, enhancing the air's capacity to retain additional water vapor from the melted beeswax. The efficiency of the solar-powered wax melter was influenced by macroclimatic conditions, incident solar radiation, ambient temperature, and relative humidity. The first system exhibited an average efficiency of 44.1%, while the second system achieved an average efficiency of 59.2%. These findings underscore the direct correlation between system efficiency, solar radiation intensity, and ambient temperature.

Authors' contributions

The authors have contributed equally to this work.

Availability of data and materials

None available.

Declaration of ethics approval and consent to participate

All authors have complied with the ethical guidelines of the journal.

Consent for publication

All authors have approved this manuscript for publication.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Conflict of interest

We certify that there is no conflict of interest regarding our paper. Additionally, this manuscript has not been previously published. We are interested in obtaining the copyright for your journal.

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