Turkish Journal of Agricultural Engineering Research

https://dergipark.org.tr/en/pub/turkager
https://doi.org/10.46592/turkager.1343229

Turk J Agr Eng Res
(TURKAGER)

ISSN: 2717-8420
2023, 4(2), 203-224

Research Article

Application of Solar Energy to Liquify Beewax

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Article Info

Received: 15.08.2023 **Accepted:** 10.11.2023 **Published:** 31.12.2023

ABSTRACT

This study investigates the feasibility of using solar energy to melting recycled older combs and capping wax byproducts to prepare raw beeswax. The solar-driven beeswax melter comprises a stainless-steel container, a lean-to structure featuring polycarbonate sheet covers, a wooden solar heater, and parallel arrays of PV solar panels. The research contrasts three distinct approaches for melting beeswax: the conventional water bath technique, exclusive reliance on solar energy for melting, and combining solar energy and supplementary heat from solar panels. The traditional water bath method's effectiveness and the bulk temperature of the liquified beeswax were determined. In the case of the solar-powered wax melting setups, the process efficiency, bulk temperature of the melted wax, and various macroclimatic factors such as sunlight radiation, temperature, and relative humidity were documented. Based on the experimental outcomes, the beeswax melting efficiency was determined to be 73.4% for the traditional water bath method, whereas it escalated to 85.5% and 87.2% for the solar approaches, respectively. Hence, the utilization of solar techniques for beeswax melting is recommended.

Keywords: *Capping wax byproducts, Honeybee, Melting efficiency, Solar energy*

To cite: Al-Rajhi MAI, El-Serey SM and Elsheikha AM (2023). Application of Solar Energy to Liquify Beewax. *Turkish Journal of Agricultural Engineering Research (TURKAGER), 4(2): 203-224.* *https://doi.org/10.46592/turkager.1343229*

INTRODUCTION

Recently, the pursuit of sustainable and renewable energy sources has gained significant momentum. This is due to global efforts to address climate change and diminish carbon emissions.

Among these prospects, using solar energy has emerged as a promising avenue, harnessing the sun's power to generate clean and abundant electricity. Although solar panels are commonly associated with electricity generation, solar energy has the potential to revolutionize diverse aspects of our lives, extending beyond powering residences and businesses. An intriguing application lies in the liquefaction of beeswax, a versatile and natural substance with a myriad of applications. By harnessing solar energy to melt beeswax, we have the opportunity to not only tap into a replenishable resource but also advocate for environmental awareness and contribute to preserving bee populations. Honeybees utilize wax to construct their honeycombs. When they reach a specific age, typically around 12 to 18 days, fully developed wax glands on the lower part of their abdomen commence wax production in the form of thin scales. These bees possess eight glands that are responsible for the synthesis of wax. Roughly 3.629 kg of honey is needed to yield 0.455 kg of beeswax. Beeswax holds value not only as a precious commodity but also as a potential source of significant revenue. Regarding economic worth, a kilogram of beeswax holds more value than a kilogram of honey. Managing beeswax is more straightforward than honey, as it doesn't necessitate delicate packaging and isn't categorized as a food product. This distinction results in enhanced ease of transportation and storage (Bradbear, 2009). Furthermore, beeswax boasts a wide array of applications, encompassing the crafting of polish, candles, and delicate wax sheets termed "foundation" sheets. In the contemporary landscape, a significant share of the produced wax finds use in the cosmetics industry, spanning from depilatory wax to hand and face creams, lipsticks, and diverse pharmaceutical items such as ointments, pills, and suppositories. According to research by Gemeda and Kebebe (2019), on the global market, beeswax is valued three times more per unit than honey. As the Food and Agriculture Organization (FAO, 2022) projected, global beeswax production has reached a tally of 62.166 tons, with contributions from Asia, Africa, and America standing at 51%, 26%, and 22%, respectively. In the context of Egypt, the year 2020 witnessed a beeswax production of 113 tons, alongside the import of 61 tons, amounting to a value of 242 thousand dollars.

Bees employ the creamy-colored beeswax to construct their nest combs, with the color of pure beeswax varying from white to yellow to yellow-brown contingent upon factors such as pollen proportion and propolis pigments. Extraction of wax can be achieved through two primary methods: chemical and melting, as outlined by Sin *et al.* (2014). Additionally, repurposing old honeycombs involves obtaining wax by removing smaller comb components like wax capping, frames, and hive elements before honey extraction. This introduction explores the potential advantages, challenges, and implications of utilizing solar energy for beeswax melting, highlighting an innovative and eco-friendly approach to fulfilling our wax melting requirements.

Employing solar energy for melting beeswax brings forth several notable benefits. To begin with, it offers a sustainable and renewable energy source, minimizing dependence on fossil fuels and mitigating greenhouse gas emissions. This shift towards solar energy aligns with global endeavors to combat climate change and transition towards a cleaner energy landscape. Additionally, solar-energy melting systems present an economical solution since sunlight is abundant and free, negating the necessity for expensive energy sources and reducing operational costs for beekeepers, artisans, and small-scale businesses.

The use of solar energy to melt beeswax can be achieved through diverse solar thermal technologies. Solar wax melting structures, for instance, are purpose-built setups that utilize solar collectors to capture and transform sunlight into heat energy. Frequently crafted from reflective materials or solar panels, these collectors concentrate sunlight onto a surface designed to absorb heat, generating ample warmth to effectively liquefy beeswax. Innovative designs also incorporate insulation and storage mechanisms, prolonging the molten state of the wax and enhancing productivity and convenience.

The melting point of beeswax falls within the range of 62 to 65°C, necessitating substantial energy for its liquefaction. Wax softens at 35°C, rendering it pliable. To eliminate impurities, the wax must be separated from the comb using sunlight, hot water, or steam before extraction, as elucidated by Mutsaers *et al.* (2005). The creation of melter systems involves utilizing electrical and solar heat supply technologies due to their simplicity. Aluminum or stainless-steel containers are suitable for preserving the wax's color, ensuring a non-direct contact with the heat source, according to Bogdanov (2009). Application of heat energy prompts beeswax to absorb it, resulting in the breaking of intermolecular bonds. According to Khamdaeng *et al.* (2016), the phase shift temperature range spans 18 to 32°C, with the melting point within 30 to 60°C.

Additionally, Egypt boasts abundant sunlight resources, with an annual average of 3050 hours of sunlight. The direct normal irradiation levels fluctuate between 1970 and 3200 kWh m^{-2}, and the annualized total solar irradiance ranges from 2000 to 3200 kWh m^{-2}, as documented in the solar atlas. Consequently, Egypt's solar potential stands out and can be harnessed across diverse solar energy systems and sectors. Moharram *et al.* (2022) note that this encompasses the feasibility of implementing photovoltaic (PV) or concentrated solar power (CSP) plant setups.

The microorganisms accountable for diverse bee ailments, including European foul brood (EFB), American foul brood (AFB), and Nosema, might be present within deteriorated or aged honeycombs. Among renewable energy sources, solar energy stands out due to its environmentally friendly attributes, cost-efficiency, and ample availability for a significant portion of the year, coupled with manageable radiation intensity. Given the scarcity of investigations on the application of solar melting systems for beeswax recycling in Egypt, this study aimed to determine an efficient approach for wax liquefaction. The central goal was to yield top-notch wax blocks suitable for local utilization or exportation, fostering successful business endeavors.

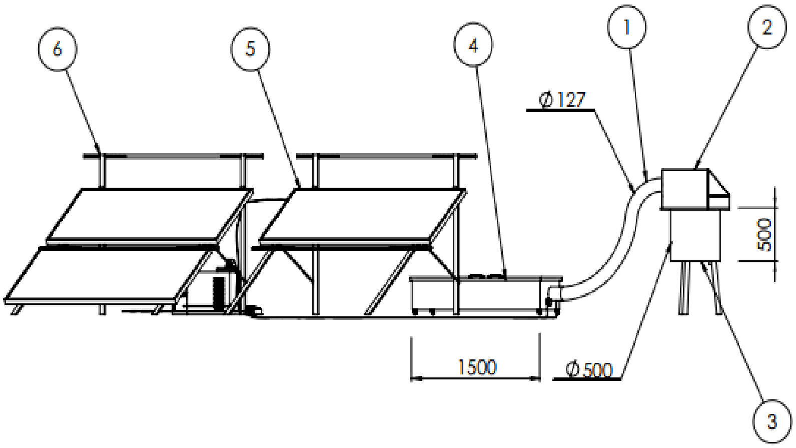
MATERIALS and METHODS

The trials were carried out at Damietta University's Faculty of Agriculture, situated at geographical coordinates of 31.4224°N latitude and 31.6575°E longitude. The research was conducted from August 30 to September 12, 2022, with the primary aim of examining how solar energy influences the process of liquefying raw beeswax. The wax melting took place during daylight hours, and temperature assessments were conducted from 07.00 to 17.00 to capture the temperatures within and outside the experimental setup, alongside any detected fluctuations in these measurements.

Materials

Unclean beeswax was procured from mature brood frames, the remnants left behind after heather pressing, and the wax that encases the cells. While cappings produce pristine wax, the beeswax derived from aged brood combs is commonly tainted.

Employing solar energy as its energy source, a solar wax extractor is utilized to swiftly and efficiently purify beeswax, elevating the internal temperature to 68-70 °C. The solar-energy wax melter consists of the components enumerated below, as depicted in the vertical diagram in Figure 1 and the photograph in Figure 2.



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. *Illustrates the vertical perspective of the wax melter powered by solar energy.*

Figure 2. *Displays a photograph of the wax melter operated by solar energy.*

The tank, constructed from stainless-steel (3), possesses a diameter measuring 50 cm and a depth of 59 cm. The exterior surface is thermally insulated to minimize heat loss from its sides. The wax discs that have been prepared are positioned on a perforated stainless-steel tray with an area of 19.63 cm². The dimensions of the wooden framework for the Lean-to architectural Form (2) can be observed in Figure 3. Exccept the nickel-chrome-protected rear reflector, the entire extractor is enveloped in 2 mm-thick polycarbonate panels to optimize its exposure to solar energy. A solar energy meter was employed to measure the intensity of solar radiation during the experiment. It offered a precision of 10 W m^{-2}, a resolution of 0.1 W m^{-2}, and the ability to record a peak intensity of up to 2000 W m^{-2}.

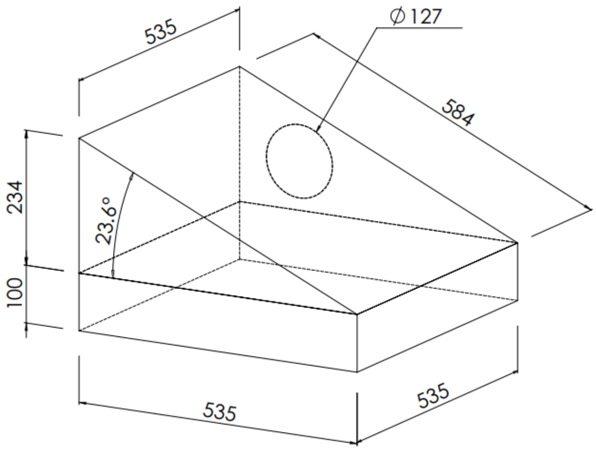


Figure 3. *Presents a schematic illustration of the Lean-to architectural structure.*

A ceramic plate was positioned beneath the thermal coil for safety and insulation purposes, to safeguard the solar heater (4). The thermal coil was attached to stainless-steel screws and placed within a wooden enclosure lined with fiberglass on the inside. This arrangement offers protection against burns and ensures effective insulation for the solar heater. The solar photovoltaic panels (5), comprised of three JSM-385M72 modules, were employed. A polycrystalline solar panel with the following specifications was utilized: designated peak power: 385 W, voltage at maximum power (Pmax): 40.29 V, current at maximum power (Pmax): 9.56 A, open-circuit voltage: 48.98 V, current under short-circuit conditions: 10.11 A, Maximum Series Fuse Rating: 20 A, Power Tolerance: 0~5 W, Maximum System Voltage: IEC1500V, Nominal Operating Cell Temperature: 45±2°C, and Operational Temperature: -40°C~+85°C. These panels were installed parallel and positioned at an ideal 30° angle relative to the horizontal plane. They were firmly affixed to a rectangular metal frame.

Methods

The experiment aimed to compare the conventional water bath technique with solar energy utilization for beeswax melting. In the water bath approach, a stove-heated aluminum pan was filled with water, and a smaller aluminum pan containing 500 g of beeswax was placed in it and heated over medium heat until wax melting occurred. In contrast, the solar-powered wax melter harnessed direct solar heat to liquefy the wax, obviating the need for comb storage. This method was assessed in two ways:

firstly, solely relying on solar energy, and secondly, integrating solar power with supplementary heat from solar panels. The latter technique employed hot air with an average velocity of 0.8 m s^{-1} and a temperature of 60°C. These variations aimed to generate raw wax via the solar-powered wax melter.

The appropriate tilt angle for an inclined surface was calculated using the equations proposed by Duffie and Beckman (2013) to achieve the lean-to architectural design and optimizing solar radiation absorption. These equations provide insights into determining the most suitable angle that ensures the highest solar radiation exposure.

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

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

The geographical latitude angle (ϕ) for the research site (New Damietta) is 31.42°.

- The solar hour angle (ω) is determined using the formula 15 (Local Apparent Time - 12), where LAT denotes the local apparent time.

- The solar declination angle (δ) signifies the sun's positioning with respect to the celestial equator.

- The symbol "n" stands for the count of days following January 1st.

Assessed Parameters:

The experiment encompassed three distinct beeswax melting techniques: the traditional water bath approach, the utilization of solar energy alone for melting, and the utilization of solar energy combined with supplementary heat from solar panels. The measurements were categorized into primary and secondary segments:

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

1) The overall temperature of liquefied beeswax.
2) Efficiency of the melting process.

Secondary measurements were carried out for the solar-powered wax melter and included:

1) Duration of beeswax melting.
2) Surrounding temperature.
3) Relative humidity.
4) Received solar radiation.
5) Overall temperature of liquefied beeswax.
6) Efficiency of melting, as defined by the equation [3] (Khamdaeng *et al.,* 2016):

$$EFF\% = \frac{M_i - M_f}{M_i} \times 100 \quad (3)$$

Where: EFF% represents the efficiency of melting (%), M_i signifies the initial mass (in grams), and M_f denotes the mass of beeswax that remains after the melting process (in grams).

7) The efficiency of the solar wax melter was determined using the subsequent equation [4].

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

Where: ηc represents the system's efficiency (%), P_{out} stands for the output power (measured in watts), P_{in} indicates the input power, m denotes the rate of wax melting (in kilograms per hour), C_p signifies the specific heat of beeswax (0.476 kJ kg^{-1} K^{-1}), ΔT stands for the temperature difference (T_f - T_i), L represents the latent heat of fusion of beeswax (242.8191 KJ kg^{-1}), A_c is the collector's surface area (measured in square meters), and I_b represents the beam radiation (in watts per square meter).

Statistical Analysis

The collected data underwent analysis using Microsoft Excel, a software developed by Microsoft Corporation and headquartered in Redmond, WA, USA. The experiments were conducted over three distinct trials, and correlation analysis was employed to enhance the study's informativeness. Microsoft Excel 2016 was employed for generating the essential graphs utilized in the analysis process.

RESULTS AND DISCUSSION

Melting Approach Using Water Bath

The outcomes reveal that a phase transition from solid to liquid occurs in beeswax at an average temperature of 63.01°C. On average, it takes about 30.5 minutes to completely melt the beeswax (Figure 4). These results offer insights into the kinetics of this phase change, offering practical implications.

The efficiency of the water bath method in melting beeswax exhibited a range between 65.1% and 77.7%, with an average efficiency of 73.4%. This signifies that a notable proportion of the applied heat effectively contributes to the wax melting. The variability in efficiency values underscores how aspects such as heating rate, insulation, and container design can impact the overall efficiency of the procedure.

These findings align with prior investigations conducted by Krell (1996), Nuru (2007), and Bogdanov (2016). These studies also highlighted that the beeswax's melting point commonly falls between 61 and 66°C, ideally situated between 62 and 65°C. The convergence of results from multiple studies underscores the dependability and validity of the water bath technique for beeswax melting.

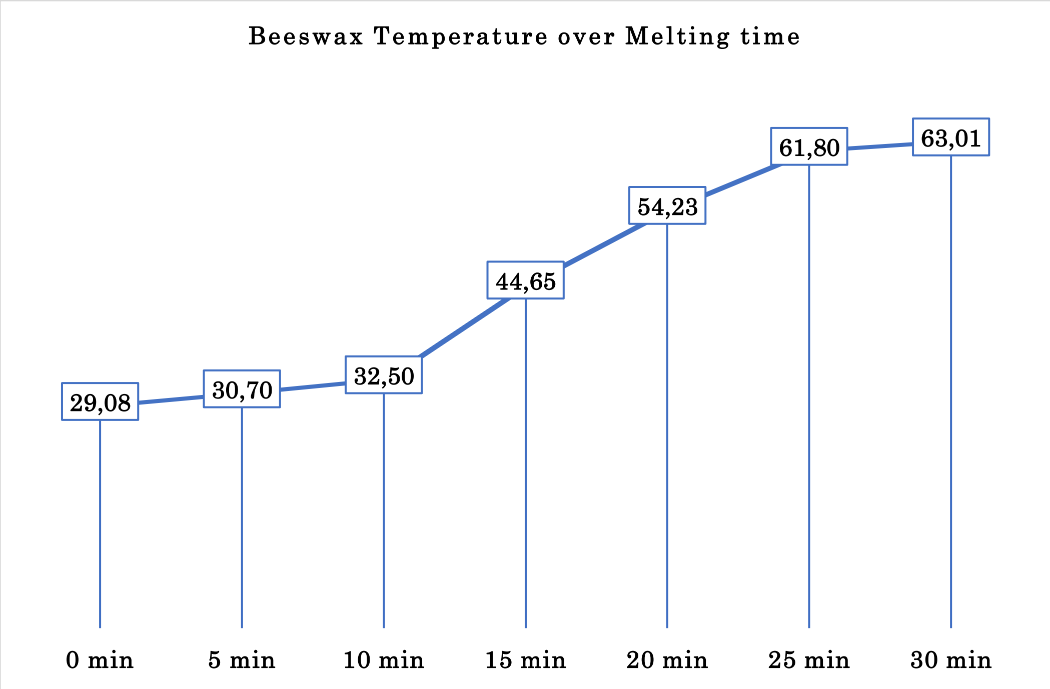


Figure 4. *Beeswax temperature during melting using a water bath.*

Utilizing Solar-Powered Wax Melter

In the initial configuration, the wax melting process spanned from 150 to 360 minutes, averaging 243.3 minutes. In contrast, the second configuration required 90 to 240 minutes, averaging at 183.3 minutes. These findings underscore the substantial reduction in melting time achievable through solar energy utilization compared to the water bath technique, which typically takes about 30.5 minutes.

The assessment of melting efficiency for the solar-energy wax melter was also conducted. In the first setup, melting efficiency ranged between 66.9% and 95.1%, with an average efficiency of 85.5%. Similarly, the second configuration exhibited melting efficiency from 81.4% to 92.1%, with an average efficiency of 87.2%. These outcomes underscore the superiority of the solar- energy wax melter over the conventional water bath method in terms of melting efficiency.

Incorporating of an external solar heater in the second configuration likely contributed to the heightened melting efficiency and reduced melting time. Sustaining an average temperature of 60°C and an average airflow velocity of 0.8 m s^{-1}, the solar heater likely amplified the heat transfer process, leading to quicker and more effective melting of the beeswax.

Solar Radiation Flux Incidence

To evaluate the solar radiation incident upon the wax melter, measurements were conducted on the solar collector's interior and exterior surfaces. During the initial six days of practical experimentation, the solar radiation incident within the collector ranged from 70 to 1037 W m^{-2}, while outside readings fluctuated between 84 and 1310 W m^{-2}. These measurements highlight the considerable range of solar energy availability and emphasize the necessity of accounting for radiation fluctuations to optimize the melting process.

The average hourly solar radiation accessible within the collector registered at 622.15 W m^{-2}, while external measurements showed 801.55 W m^{-2}. These values provide insights into the customary solar energy levels viable for beeswax melting. It's essential to acknowledge that these figures reflect the specific parameters of this study and could differ based on geographic location and time of year.

In the second configuration, the measurements within the collector spanned from 50 to 1014 W m^{-2}, with exterior readings ranging between 67 and 1190 W m^{-2}. This system's average hourly solar radiation was 776.60 W m^{-2} outdoors and 607.3 W m^{-2} indoors. These values underscore the inherent variability in solar radiation and the importance of optimizing the appproach to capture and utilize energy effectively.

The 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 visualization offers a graphical representation of the dynamic nature of solar energy and the challenges associated with maintaining consistent heat input during the beeswax melting process.

The results emphasize the significance of vigilant monitoring and control of the solar energy system to accommodate variations in incident radiation. Approaches like 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.

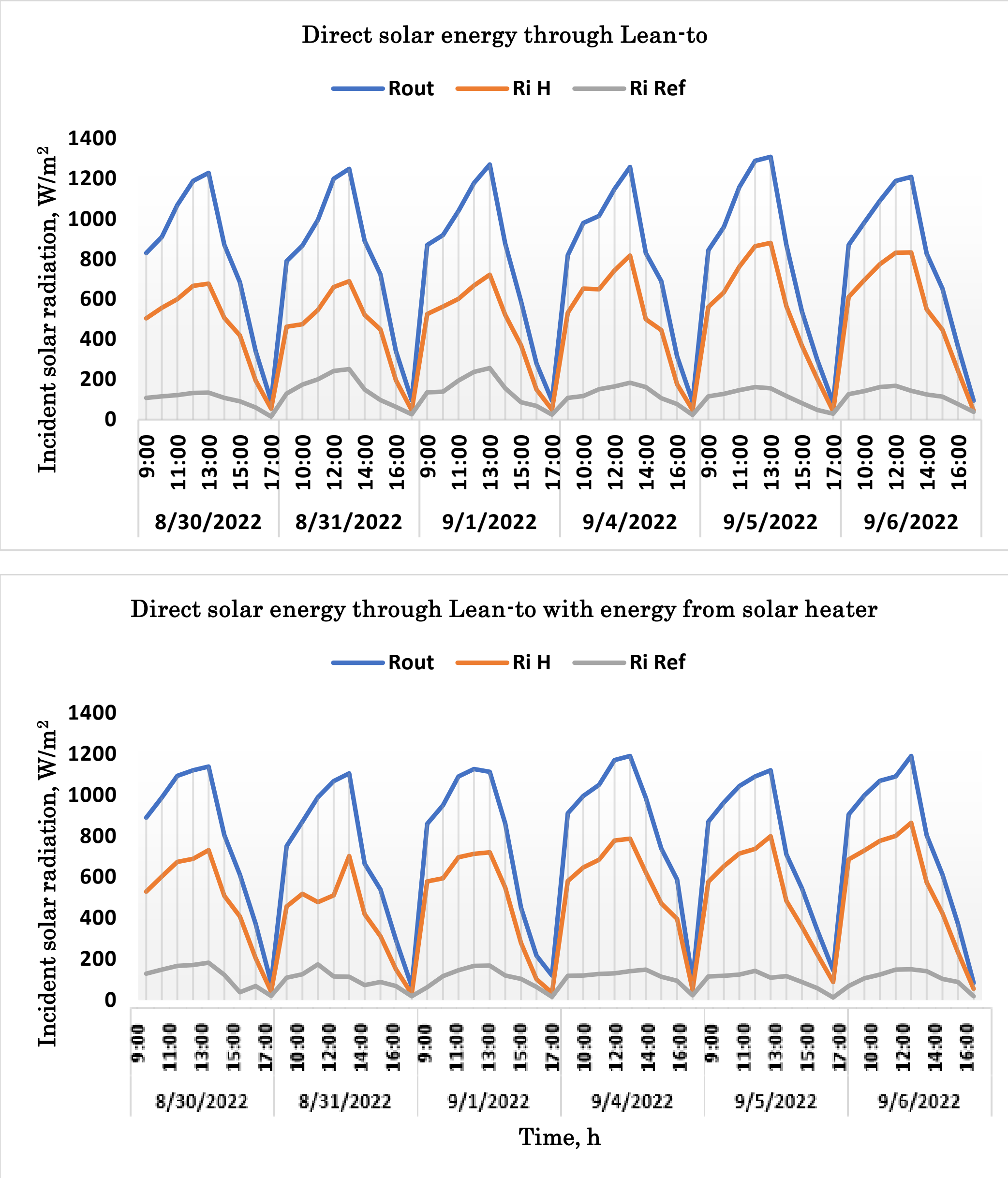


Figure 5. *Illustrates the daily variations in incoming solar radiation, both within and outside the collector, as well as the reflected radiation from the vertical-back wall during the experimental work for the two systems.*

Figure 6, as mentioned in the results section, likely portrays a visual representation of the connection between the solar radiation entering the collector and the solar radiation measured externally. This connection offers valuable insights into how effectively the transparent polycarbonate cover enables solar radiation to enter the collector.

Examining the relationship between the solar radiation entering the collector and the external measurements is pivotal for comprehending the efficiency of harnessing solar energy. This analysis can yield valuable information about the ability of the polycarbonate cover to transmit and effectively capture solar energy for the wax melting process.

Furthermore, the correlation between solar radiation within and outside the collector can help identify potential losses or inefficiencies in the system. Disparities in solar radiation values may suggest factors like reflection, absorption, or dispersion of solar energy within the collector.

By meticulously adjusting the transparent polycarbonate cover's design, researchers and engineers can aim to maximize solar energy capture and minimize losses, thus improving the overall efficiency of the beeswax melting process. The results presented in this study originate from a straightforward power regression analysis conducted to establish a relationship between the changes in incident solar radiation within a solar collector and the 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:

Equation: $y = 0.7628x + 10.763$ ($R^2 = 0.9788$)

This equation signifies 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 ($R^2= 0.9788$) indicates that this equation effectively explains and predicts changes in solar radiation within the collector based on external conditions. The strong correlation suggests 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:

- Equation: $y = 0.7838x + 1.5014$ ($R^2= 0.9724$)

Once 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, implying 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, assisting 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.

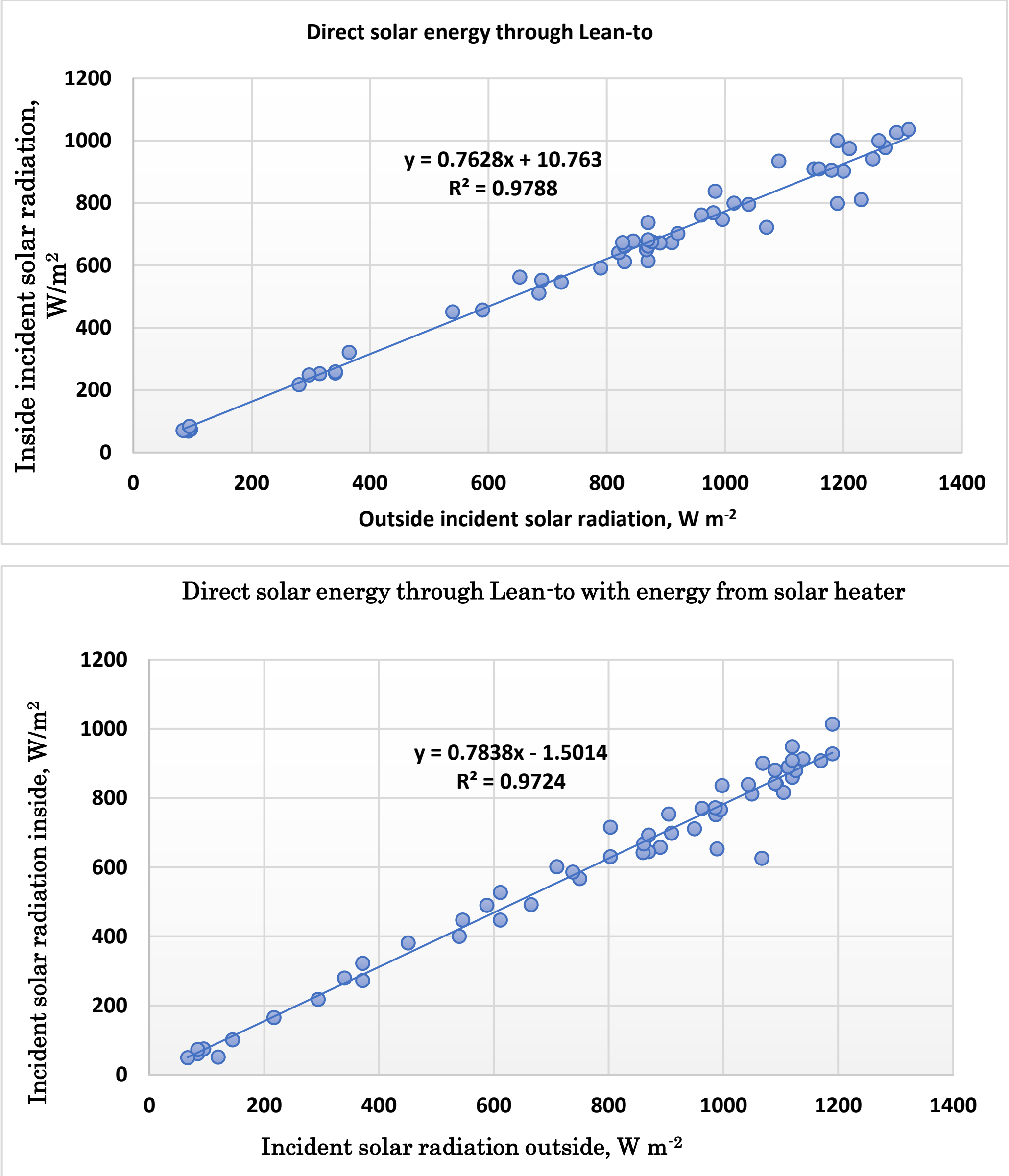


Figure 6. *Illustrates the relationship between the solar radiation incident within the solar collector and the solar radiation incident outside for the two systems.*

Environmental Temperature and Humidity Effects

The outcomes underscore the significance of temperature and humidity in the phase transition of a substance from a solid to a liquid state. The melting process involves raising a solid's internal energy, generally through heat application, which enables the solid to reach its melting point and undergo fusion (Sofekun *et al.*, 2018). In the case of beeswax, heat application is crucial for facilitating its transition to a molten state, necessitating the addition of latent heat, specifically the heat of fusion.

Throughout the experiment, the researchers documented the average hourly ambient temperatures outside and within 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 provide insights into the temperature conditions prevailing around the wax melter during the experimentation.

The outcomes also reveal the percentage rise 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 illustrate the efficiency of the lean-to solar collector technique in significantly elevating the indoor ambient temperature within the wax melter.

Moreover, the researchers observed a significant influence of the indoor ambient temperature on the overall temperature of the beeswax by employing the lean-to solar collector technique under specific experimental conditions. It is plausible that Figures 7 and 7 visually represent this correlation, illustrating the link between indoor ambient temperature and beeswax temperature. The data analysis corroborated these observations, affirming the connection between indoor ambient temperature and beeswax melting temperature.

These findings underscore the pivotal role of ambient temperature in the beeswax melting process. Higher indoor ambient temperatures within the wax melter lead to more efficient heat transfer and subsequent beeswax melting. The lean-to solar collector technique, which capitalize on solar energy and fosters an elevated indoor ambient temperature, offers a mechanism for achieving effective beeswax melting.

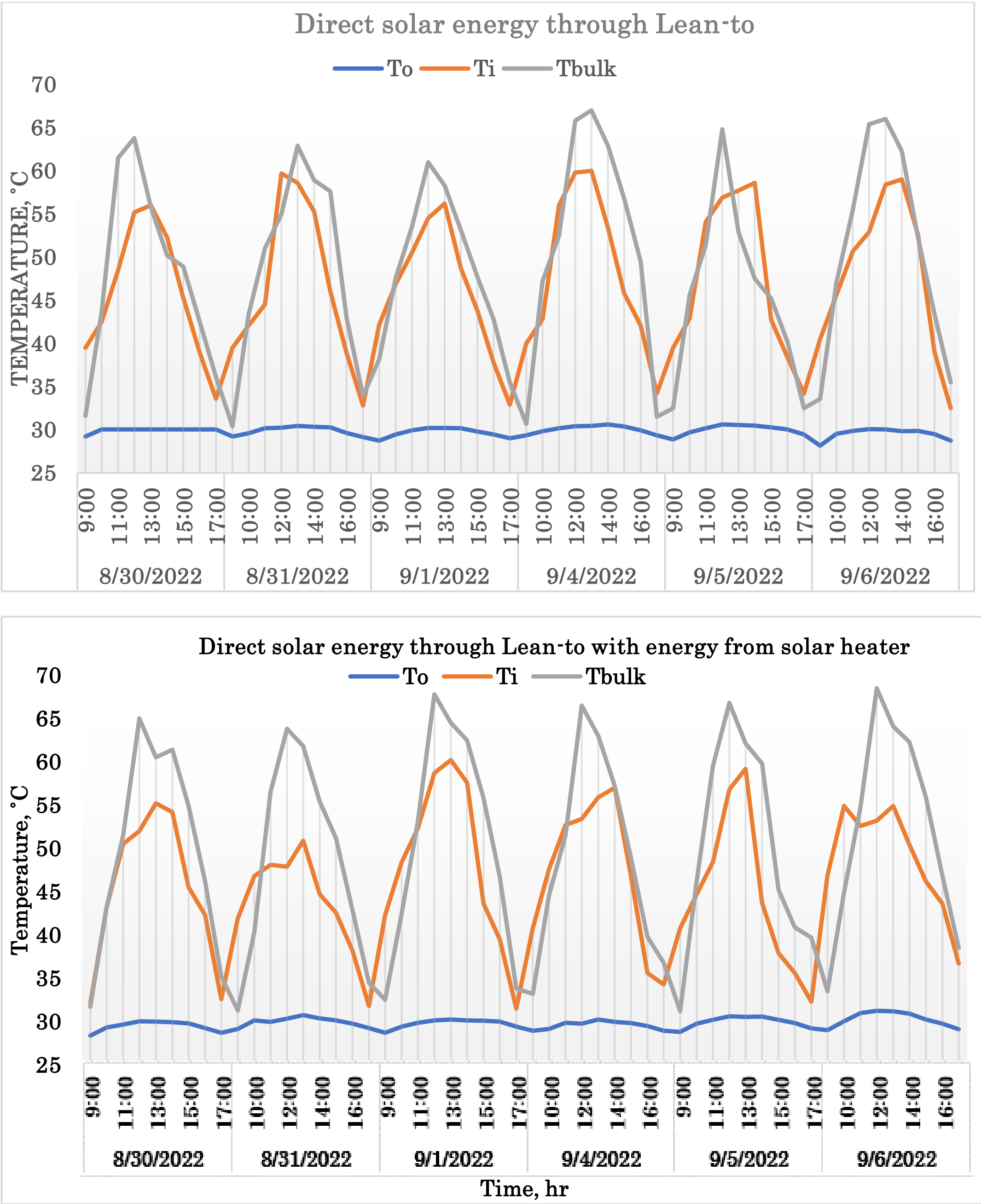
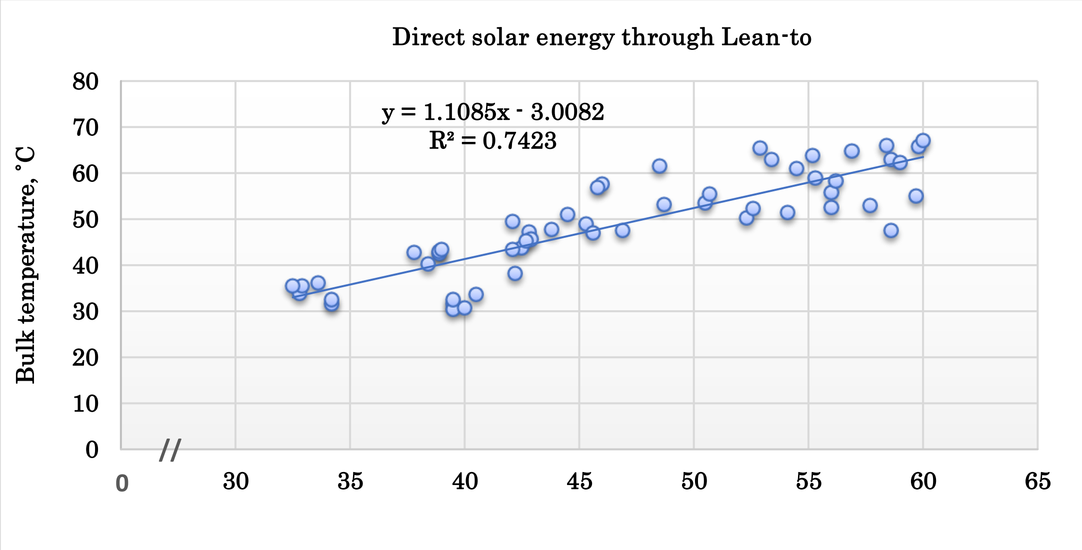


Figure 7. Illustrates the daily variations in bulk and ambient temperatures both within and outside the solar collector throughout the experiment for the two different systems.



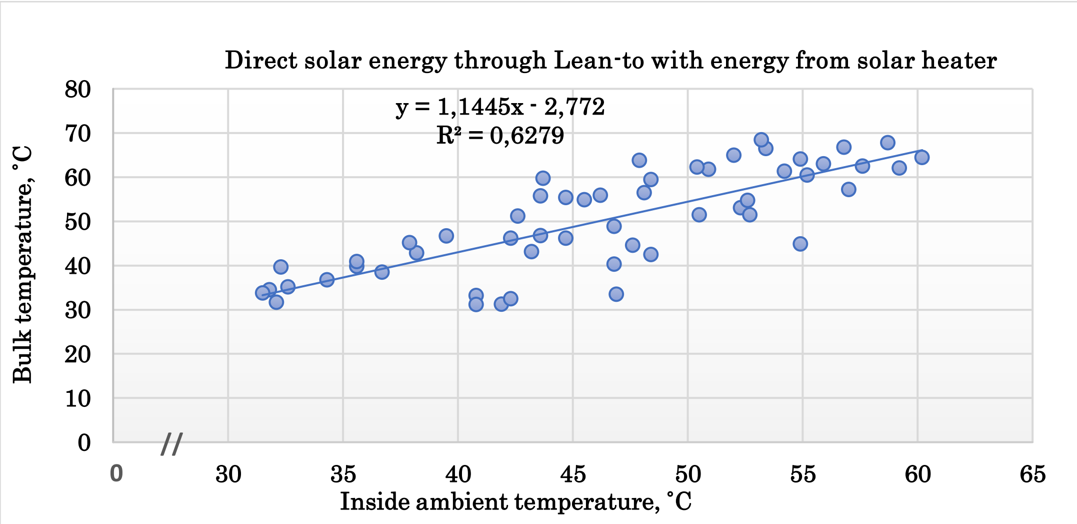


Figure 8. *Depicts the relationship between the bulk temperature of beeswax and the inside ambient temperature within the Lean-to solar collector for both of the studied systems.*

In the initial system, the solar collector's average indoor relative humidity was 36.1%, while the external humidity was 68.71%. Similarly, for the second system, the respective figures 8 were 38.28% and 71.24%. These measurements reveal the disparity in humidity levels between inside and outside the wax melter during the experiment.

The solar extractor, an integral part of the solar collector system, was crucial in diminishing indoor relative humidity. In the first system, the solar extractor effectively lowered the indoor relative humidity within the solar collector by approximately 32.61%. Similarly, in the second system, it reduced the indoor relative humidity by around 32.96%. These outcomes highlight the instrumental role of the solar extractor in maintaining lower indoor relative humidity levels within the wax melter.

These findings represent the outcomes of a power regression analysis that explores the relationship between the change in bulk temperature of beeswax and the inside ambient temperature within a Lean-to solar collector for two distinct systems: one operating without additional energy input and another with energy input from a solar heater. The regression equations derived 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 regression equations express the mathematical relationship between the bulk temperature (y) of the beeswax and the inside ambient temperature (x) within the Lean-to solar collector for the two studied systems. They provide a predictive tool to estimate the bulk temperature based on the inside ambient temperature for each system.

The R^2 value serves as an indicator of how well the regression equation aligns with the data points. It signifies the proportion of variance in bulk temperature that can be attributed to changes in the inside ambient temperature. In both cases, R^2 values are supplied to gauge the goodness of fit. A higher R^2 value suggests that the regression equation provides a better fit for the data. Notably, the system operating without additional energy input (direct solar energy through Lean-to) exhibits a slightly higher R^2 value (0.7423) in comparison to the system with energy input from a solar heater (0.6279). This implies that the bulk temperature of beeswax in the first system is more significantly influenced by changes in the inside ambient temperature.

These results bear practical significance in the realm of solar energy collection and utilization. They offer insights into how the bulk temperature of beeswax, likely utilized as a heat storage medium, responds to variations in the inside ambient temperature. Engineers and researchers can leverage this information to optimize the performance of Lean-to solar collectors under different energy input scenarios.

Conclusively, these regression outcomes provide valuable insights into the correlation between bulk temperature and inside ambient temperature in Lean-to solar collector systems. This knowledge lays the foundation for further research and optimization endeavors within the field of solar energy collection and utilization.

Figure 9 provides a visual representation of the fluctuations in indoor and outdoor relative humidity levels within the solar collector. This graphical illustration offers a clear insight into the divergence in humidity conditions and the efficiency of the solar extractor in reducing indoor relative humidity.

The impact of relative humidity on the beeswax melting process warrants consideration. Elevated humidity levels can impact heat transfer efficiency and lead to increased moisture content in the beeswax, potentially altering its characteristics. Thus, reducting indoor relative humidity levels within the wax melter contributes to sustaining optimal conditions for effective and consistent beeswax melting.

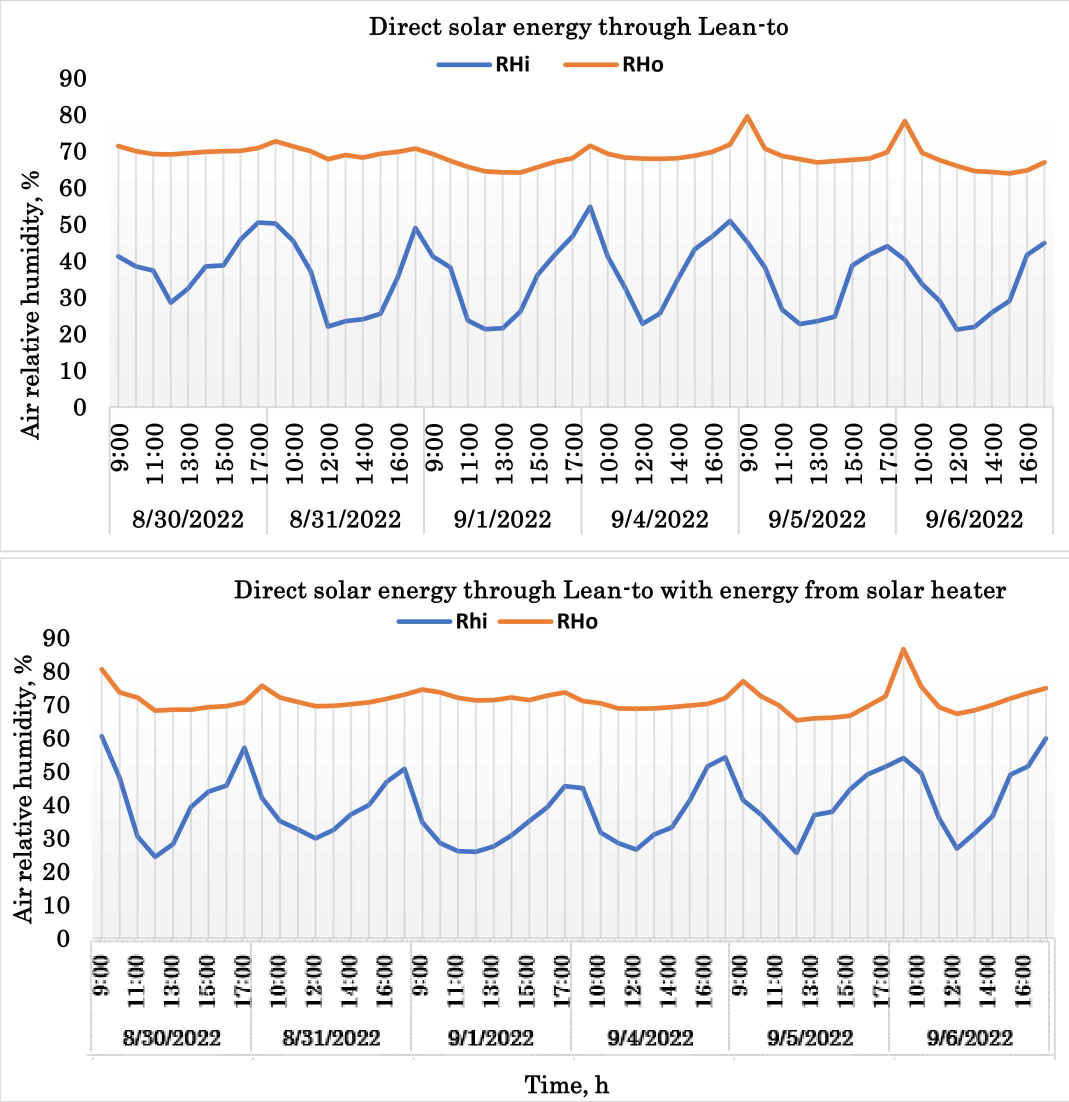


Figure 9. Daily fluctuations in relative humidity inside and outside solar collector during the experimental work for the two systems.

The study's outcomes reveal a distinct relationship between air temperature and relative humidity, particularly during daylight hours. These two factors are interconnected, and alterations in air temperature can impact the air's capacity to hold moisture.

Furthermore, the study showcases the solar collector's potential to decrease indoor relative humidity in contrast to outdoor relative humidity, while simultaneously elevating indoor temperatures beyond outdoor temperatures. This observation indicates that the solar collector establishes an environment where the air inside becomes drier and warmer than the external surroundings.

The decline in indoor relative humidity within the solar collector can be attributed to components like the solar extractor within the collector system. By effectively lowering relative humidity, the collector establishes conditions less conducive to moisture retention. This proves advantageous for beeswax melting, as reduced relative humidity prevents excessive moisture absorption by the wax, thus preserving its intended qualities.

At the same time, the rise in indoor temperature surpassing the outdoor temperature inside the solar collector accelerates the melting process. The heightened temperature creates an environment more conducive to beeswax melting, reducing the time needed for complete melting. The increased indoor temperature facilitates efficient heat transfer, ensuring rapid achievement of the beeswax's melting point.

Additionally, the increased air's capability to retain additional water vapor from the melted beeswax implies that the warmer and drier air within the solar collector can effectively absorb and carry away the moisture released during melting. This aids in averting moisture buildup and ensures the melted beeswax retains its intended consistency and attributes.

These findings emphasize the advantages of employing a solar collector for beeswax melting. The solar collector raises indoor temperatures, expediting the melting process, and diminishes relative humidity, preventing moisture-related concerns and upholding the quality of the melted wax.

System Effectiveness

The study outcomes shed light on the efficiency of two distinct systems employed for beeswax melting. The initial system exhibited efficiency ranging from 31.4% to 61.6%, averaging 44.1%. On the other hand, the second system displayed a broader range of efficiency values, varying between 44.1% and 76.6%, with an average efficiency of 59.2%.

These efficiency measurements signify how effectively each system transforms solar energy into heat for the melting process. The second system, on average, demonstrated superior efficiency compared to the initial system, implying that it utilized available solar energy more efficiently.

It's important to note that the macroclimatic conditions surrounding the solar collector significantly impact the efficiency of the wax melting systems. Elements like incident solar radiation, ambient temperature, and relative humidity play vital roles in determining the overall efficiency of the systems.

Figure 10 likely presents a graphical depiction of the connection between system efficiency and the aforementioned factors. This visualization aids in comprehending how fluctuations in incident solar radiation, ambient temperature, and relative humidity influence the efficiency of the wax melting systems.

The correlation between system efficiency and incident solar radiation holds importance as solar energy is the primary heat source for the systems. Higher levels of incident solar radiation typically lead to increased energy input and, consequently, higher system efficiency.

The connection between system efficiency and ambient temperature underscores the significance of maintaining optimal temperature conditions for effective wax melting. Elevated ambient temperatures create a favorable environment for heat transfer, resulting in reduced melting time and improved system efficiency.

Similarly, the link between system efficiency and relative humidity highlights how moisture content in the surrounding air impacts 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.

Comprehending these correlations aids in identifying key factors influencing system efficiency and informs the optimization of wax melting systems. By accounting for 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.

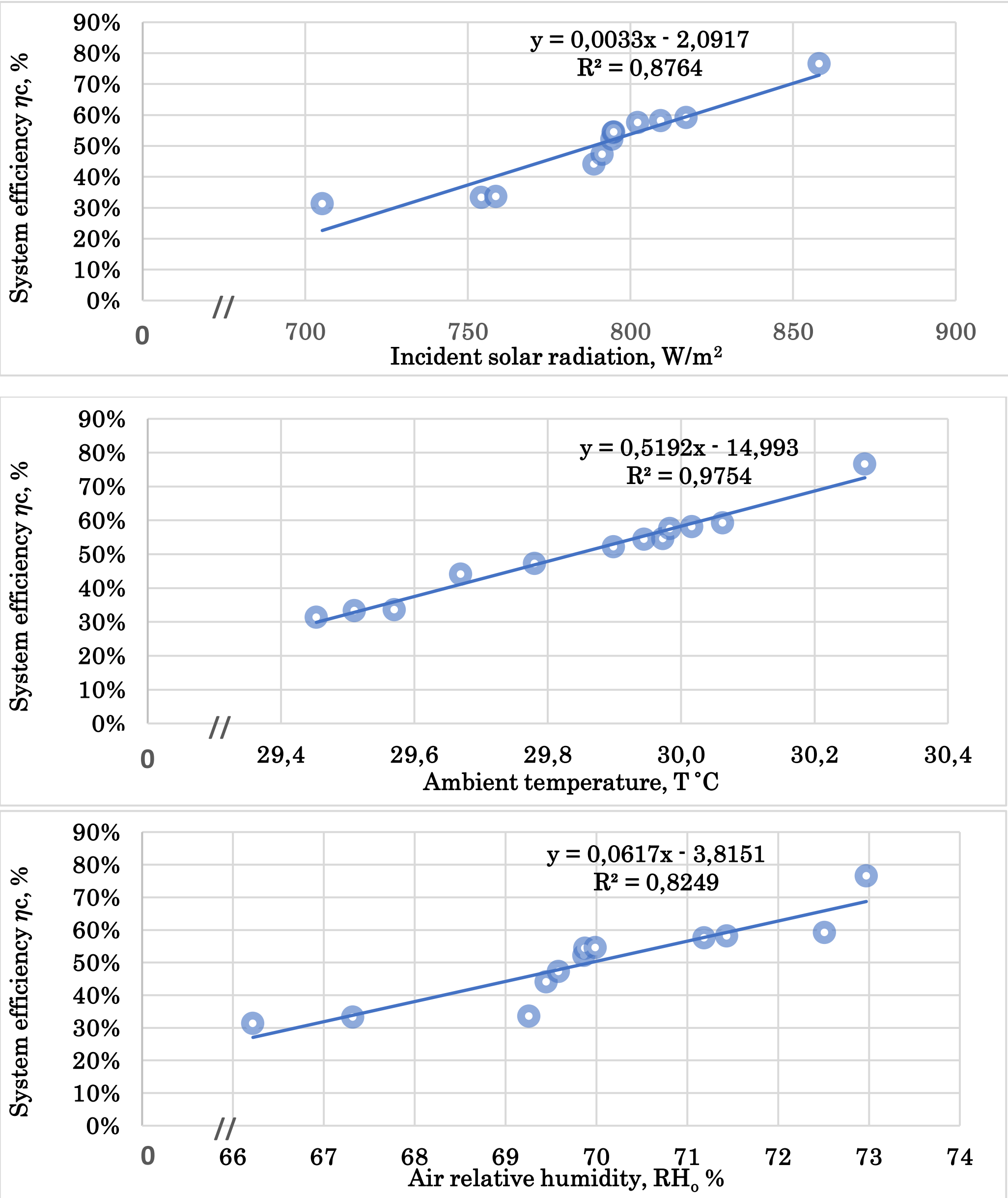


Figure 10. *Illustrates the direct correlation between system efficiency and incident solar radiation, ambient temperature, and relative humidity.*

The outcomes of the present investigation are in agreement with the research conducted by Khan *et al.* (2019), who investigated the relationship between daily candle production and variations in average solar radiation measured in W/m². In their study, Khan et al. employed solar energy to heat and liquify beeswax, a process akin to the one explored in the current study.

The results obtained by Khan et al. revealed a direct link between solar radiation intensity and the efficacy of the melting process. This implies that higher solar radiation levels lead to more effective wax melting. The findings of the present study, which establish a connection between system efficiency and incident solar radiation, concur with these outcomes.

Furthermore, Khan *et al.* (2019) also identified a connection between ambient temperature and the efficiency of the melting process. The findings of the present study, which indicate the impact of ambient temperature on the beeswax melting process, are in harmony with this earlier research.

These consistent findings among studies provide substantial evidence that solar radiation and ambient temperature are crucial factors in the wax melting process. Utilizing higher solar radiation levels and maintaining elevated ambient temperatures contribute to more efficient and effective melting of beeswax.

The alignment of these results underscores the significance of incorporating solar radiation and temperature considerations into the design and optimization of wax melting systems. Maximizing the utilization of solar radiation potential and maintaining suitable ambient temperature conditions can substantially enhance the efficiency and productivity of candle production and other applications reliant on melted beeswax.

The primary objective of this study was to quantitatively analyze and establish the relationships between system efficiency and key environmental parameters. Understanding these relationships is essential for optimizing energy systems and adapting 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. In the case of 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 $y= 0.0617x - 3.8151$, and the R^2 is 0.8249.

The linear form of these equations indicates a direct and proportional relationship between system efficiency and each environmental variable. Calculating the R^2 values allowed us to assess how well these regression models fit the data. These values represent the proportion of variance in system efficiency that can be explained by changes in the respective environmental variable.

The correlation between system efficiency and incident solar radiation is positive but moderately weak ($R^2= 0.8764$). This suggests that while solar radiation impacts efficiency, other factors may also contribute to variations in system performance. On the other hand, 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. System efficiency and air relative humidity also show a positive correlation, albeit slightly weaker compared to temperature ($R^2= 0.8249$). Air relative humidity plays a role in system efficiency but to a lesser extent than temperature.

These results hold significant value for engineers and energy system designers. They can use these regression equations to optimize energy systems, taking into account how incident solar radiation, temperature, and humidity affect efficiency, leading to more efficient and reliable energy systems.

The robust correlation between system efficiency and ambient temperature underscores the importance of implementing climate adaptation measures. Strategies such as temperature control, cooling, or insulation can help maintain optimal efficiency under varying temperature conditions.

Furthermore, these relationships can be leveraged for energy forecasting and system planning. Understanding how system efficiency responds to environmental changes enables more accurate predictions of energy production and consumption, facilitating efficient energy management.

CONCLUSION

This study compared between two distinct beeswax melting approaches: the conventional water bath method and a solar-powered wax melter. The water bath method exhibited an average efficiency of 73.4% and required approximately 30.5 minutes on average to melt the beeswax. Conversely, the solar-powered wax melter demonstrated higher efficiency, averaging 85.5% and 87.2% for the two examined systems. Although the solar-powered method had longer melting times, ranging from 90 to 360 minutes, its superiority over the traditional method was evident.

The incident solar radiation flux played a pivotal role in the performance of the solar-powered wax melter. However, reliance on solar energy demands careful control due to fluctuations caused by factors such as clouds, fog, and time of day. The experiment documented changes in incident solar radiation inside and outside the solar collector, ranging from 70 to 1037 W m^{-2} and 84 to 1310 W m^{-2}, respectively. Similar fluctuations occurred in the second system, 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 critical role in determining the amount of solar radiation entering the collector.

Ambient temperature and relative humidity also impacted the melting process. The average hourly ambient temperatures recorded outside and inside the solar collector were about 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 elevated the indoor temperature beyond the outdoor temperature, leading to shorter melting durations. Relative humidity inside the solar collector decreased by around 32.6% to 32.96% compared to outdoor relative humidity, enhancing the air's capacity to retain extra water vapor from the melted beeswax.

The efficacy of the solar-powered wax melter was influenced by macroclimatic conditions, incident solar radiation, ambient temperature, and relative humidity. The first system demonstrated 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.

DECLARATION OF COMPETING INTEREST

The authors hereby declare that there is no conflict of interest what so ever on this work.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Mohamed Ali Ibrahim Al-Rajhi: Conceptualization, design, data collection, manuscript drafting.
Sara Moufied El-Serey: Methodology refinement, data analysis, manuscript review and editing.
Ahmed Mohamed Elsheikha: Project supervision, guidance, manuscript review for scientific rigor.

ETHICS COMMITTEE DECISION

This article does not require any ethical committee decision.

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