Performance Evaluation of a Solar Heating System for Poultry Houses

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Abstract: The aim of this study was to examine the efficiency and profitability of using solar energy in heating poultry rooms compared to traditional heating systems. Two identical poultry rooms were prepared and used for 40 days for raising broilers. The first room was heated by traditional heating (gas) and the other room was heated by a developed solar heating system. A solar air heating system was used to heat the room during daytime. A solar water heating system was used to heat up the water during daytime. The heated water was stored in a storage tank and used to heat the room during nighttime. 50 chicks were placed in each room, and their water and feed requirements were supplied throughout the day. All required data were recorded during the experiment, and the thermal performance of the developed solar heating systems was analyzed. The results obtained in this study revealed that renewable energy has a high efficiency in heating poultry houses with high efficiency, low cost and ecofriendly. The average overall thermal efficiency of the solar air and water heaters were 52.6% and 52.1%, respectively. The average energy stored in the water during the six weeks of the experiment was 64.3 MJ/week with a total of 386 MJ. The relative humidity in the room heated by solar energy maintained under 45%. Meanwhile, the relative humidity in the room heated by traditional gas heating was higher than 58% during the day. The conversion rate for solar heating rooms was 1.35 compared to the traditional heating rooms which was 1.43. Therefore, this study recommends the use of renewable energy technologies in heating poultry houses, given their practical importance in increasing productivity and reducing production costs compared to traditional heating systems.

Key words: Poultry house; renewable energy; heating; solar heaters; conversion rate.

INTRODUCTION

In recent years, Egypt's poultry industry has emerged as a key pillar of national food security. The country produced approximately 1.8 billion broiler chickens in 2019 (FAO, 2020), with projections indicating this could rise to 2 billion by 2025. Notably, imports constitute just 5% of total poultry consumption, demonstrating Egypt's near self-sufficiency in poultry meat production at current consumption levels. Therefore, research to solve problems facing poultry industry in Egypt is a vital issue at the present time. Innovating cutting-edge technologies for reducing the overall cost and increasing production efficiency becomes an essential need for farmers, processors and consumers. Another major challenge stems from the surging global demand for poultry meat and eggs, projected to double by 2050 (Alexandratos and Bruinsma, 2012). While advances in poultry housing systems have been implemented to meet this demand, these innovations often escalate energy consumption, leading to higher CO_2 emissions and increased production costs. Poultry housing requires precise management of ventilation, lighting, and temperature to optimize production. Proper ventilation is essential to maintain warmth, particularly during the brooding period (Renaudeau *et al.,* 2012). However, poultry farmers often struggle to regulate indoor temperatures during extreme summer and winter conditions. This is especially critical for chicks in their early growth stages, as they are highly sensitive to temperature fluctuations (Costantino *et al.,* 2018). In summer, appropriate steps should be taken to avoid overheating and heat stress. In winter, heating should be used to provide suitable temperature for the chicken growing. Heating is vital in the first week for the development of the chicken before they become able to regulate their own body temperature. In their six-weeks breeding period, chickens are highly sensitive to the surrounding temperature that may harm their performance if low (Vigoderis *et al.,* 2009). Moreover, as the chicken develops sufficient size and hair coverage, heating requirements decrease gradually with advanced stages in breeding according to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommendations (ASHRAE, 2011). Breeding temperature on the first day of life should be controlled ranging from 30 to 32°C at the eye level of the chicks. Thereafter, the temperature should be dropped by 2-3°C each week, down to ~21-23°C at the age of 7 weeks (Donald, 2010; Kharseh and Nordell, 2011). In the poultry industry sector, a large amount of energy is needed for lighting, heating, ventilation and cooling and running electric motors for feed lines. One of the

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large costs of production that farmers can influence is that of alternative heating and cooling systems. The heating process is a mainstay in poultry raising and the most important factors for the success of production as the heating process increases the final costs of production. Poultry producers require 60-205 million Watt per year per house for heating needs depending on specific location, bird size, and insulation of housing (Simpson *et al.,* 2005). Moreover, poultry houses require substantial energy for climate control. In laying hen farming, ventilation alone consumes 15–20 kWh m^{-1}, accounting for 58.9% of total electrical energy use. For broiler production (meat chickens), nearly all energy is dedicated to climate control (76% of electrical energy and 96% of thermal energy). According to ElZanaty (2014), around 350,000 tons of fuels are need per year for heating purposes of the broiler poultry sector in Egypt and this number is approximately higher or lower in most of the Arab countries. The large-scale use of non-renewable energy results in the emission of tremendous amounts of carbon dioxide, which traps the incoming heat coming to earth, thus making the earth warmer. Furthermore, the shortages in conventional fuels along with the continuous rise in their prices have led to an increased emphasis on using solar energy as an alternative source of energy (Kishk *et al.,* 2019). Consequently, recent studies are moving towards implementing renewable energies in the poultry production field, where solar, wind and biomass are commonly considered. Utilization of solar energy to heat poultry houses in Egypt has a great potential, as, the annual daily average solar radiation on a horizontal plane in Egypt is 8 $kWm^{-2}day^{-1}$ and the measured annual average daily sunshine duration is approximately 11 h (El-Beltagy *et al.,* 2007). As a renewable energy source, solar energy proves more practical than wind and biomass due to its consistent availability and higher power density (Dunkley, 2011). While heating systems in poultry houses have been widely studied, few focus on solar energy as a heat source. However, in other heating applications, solar energy has demonstrated cost-effectiveness by reducing reliance on electricity, diesel, or natural gas. Harnessing solar radiation can fully or partially meet heating demands, significantly cutting conventional energy consumption. (Fawaz *et al.,* 2014). Solar air heater (SAH) is one of the solar devices that can be built with readily available materials, which keep its fabrication cost very low. It can be installed anywhere, and its maintenance and operational cost are very low. Also, SAH has no corrosion problem and air leaks do not stop the device from working (Belmonte *et al.,* 2016). Due to these advantages, solar air heaters have increasingly emerged as one of the most efficient solutions to address environmental concerns stemming from excessive fossil fuel combustion. They are now widely utilized across various industrial sectors, including building heating and ventilation, agricultural product drying, liquid desiccant dehumidification, and solar chimney power plant systems (Kumar *et al.,* 2017; Kabeel *et al.,* 2017; Khanlari et al., 2020; Vijayan *et al.,* 2020; Chen *et al.,* 2021; Kannan *et al.,* 2021). On one hand, solar water heaters (SWH) are used to utilize the solar energy for water heating to be used for different purposes (Omojaro and Aldabbagh, 2010). SWH technology has been well developed and can be easily implemented at low cost (Xiaowu and Ben, 2005). Solar water heaters offer several advantages, including simple design, ease of construction, and low maintenance requirements. As an environmentally sustainable technology, they operate with zero greenhouse gas emissions during use (Maraba, 2012). Solar water heaters are widely used for low temperature applications especially in domestic areas (Patil and Deshmukh, 2015). To date, there are no major studies of the potential application of solar energy for poultry farming in Egypt. The use of solar energy will reduce production costs and increase profit margin in this area in addition to preserving the environment by reducing the burning of fuel. Accordingly, the main aim of this study was to investigate the efficiency and performance of a solar heating system in heating the poultry house. Also, the thermal performance and energy consumption of the solar heating system is compared to the traditional heating systems.

MATERIAL AND METHODS

A solar heating system was developed and used for the poultry house and compared to the traditional heating system. Two solar heating systems were designed and constructed, namely solar water heating system (for nighttime heating) and solar air heating system (for daytime heating).

1. Solar water heating system (SWHS):

A solar water heating system (SWHS) was designed and constructed. The SWHS was used to heat the water using solar energy and circulate the hot water to heat the poultry room during the nighttime. The constructed SWHS consisted of four main parts: solar water heater (collector), centrifugal pump, storage tank and heat exchanger (installed in the room) as shown in Figure (1). A flat plate with zigzag pipe solar water heater type was constructed in this study. The SWH used in this study consisted of five components as shown in Figure (2): (a) The panel box: a rectangular plywood box (10 mm thickness) with dimensions of 1.5 × 1 m and 0.1 m side height, with 1.5 m^2 net upper surface area. (b) The absorber plate: a 1 mm thick aluminum sheet was used as absorber plate. The sheet had dimensions to fit the inner dimensions of the panel box and to easily fix inside the box at the bottom. It was painted with matt black paint to be able to absorb a maximum amount of solar radiation on its upper surface. (c) The zigzag copper pipe: a copper pipe diameter of 6 mm was used to make a zigzag channel in the solar collector with a total length of 20 m. The zigzag channel is fixed over the aluminum absorber plate with aluminum clips. The copper pipe was also painted matt black. (d) Insulation material: to minimize the heat loss, the gaps between the absorber plate and the wooden box was packed with Styrofoam (50 mm thick and 0.04 ($Wm^{-1}K^{-1}$) thermal conductivity). (e) Glass cover: a clear glass cover with a 3 mm thickness was used to cover the solar panel box to minimize the reflection of radiation and heat losses. Two solar water heaters with a total surface of 3 m^2 were constructed and used in the water heating system. The heaters were connected to an isolated storage tank via a centrifugal water pump to store the water heated during the daytime. Polyethylene storage tank with a volume of 0.5 m^3 was used. The tank was insulated by styrofoam layers to minimize the heat energy loss. During the night, the circle with solar heaters is closed and the storied hot water is pumped to the poultry room via heat exchanger.

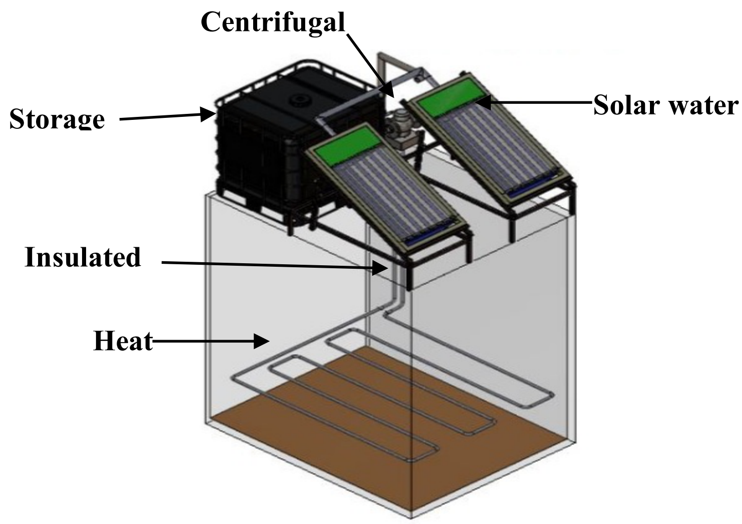

Figure (1): Solar water heating system (SWHS) installed in the poultry house.

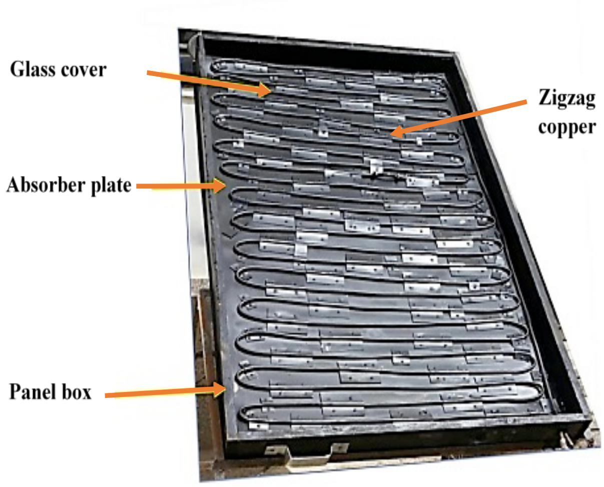

Figure (2): Flat plate solar water collector component

2. Solar air heating system (SAHS):

A solar air heating system (SAHS) was designed and constructed. The SAHS was used to heat the air using solar energy and directly pumped the heated air to the poultry room during the daytime. The constructed SAHS consists of three main parts: solar air heater (collector), air blower and air distributor as shown in Figure (3). The SAH used in this study consisted of the same components of the SWH described above with the same dimensions and configuration of panel box, absorber plate, insulation material, and the glass cover. The only difference was in the zigzag copper pipes. In the SAH larger diameter copper pipes were used with a diameter of 2.54 cm (1 inch). The length of the copper tube was 9 m and it consisted of 6 openings with 25 cm between each opening (Figure 4). One solar air heater (collector) was constructed and placed on the roof of the experiment room in a south direction at an angle equal to the latitude of the experiment area to achieve the maximum benefit from the solar radiation falling on it. So, the solar collector was inclined at 31° to maximize possible solar radiation flux incident on it. The solar air heater connected to the air blower to directly drive the heated air to the poultry room during the daytime through an air distributor.

3. Poultry house preparation:

The experimental work of this study was carried out at a private poultry farm located in Ismailia city, Egypt in the period from 15th January to 23 February 2021. During this period in Egypt, the air temperature records the lowest values through the whole year, where the air temperature reaches about 1 °C at night. Accordingly, heating systems should be used to provide the suitable temperature for the chicks in the poultry house. Two identical poultry rooms were prepared and operated during this research work. The poultry rooms were built from local materials of bricks and concrete. The room dimensions were 3 m height, 2 m width, 2.5 m length with net surface area of 5 m^2 and 15 m^3 volume with a capacity of 50 birds to be suited with the recommended average bird density of 10 birds/m^2 (Acres, 2009; Mendes *et al.,* 2004; Škrbić *et al.,* 2009). The longitudinal direction of the rooms is located from north to south direction. The poultry rooms were designed to preserve the health of poultry, and they were continuously cleaned and disinfected. The two rooms are installed with proper lighting systems. The floor of the two rooms was covered with a layer of sawdust (3 kg/m^2) and sufficient feeder pans, and water drinker bells were distributed in the rooms. After preparing the two identical rooms, they have been used for poultry production under two different heating systems, namely traditional heating and solar heating systems. For traditional heating, a gas heater was installed inside the first room and connected to the gas source to make sure the connections are safe, then the heater was tested to ensure its safety and performance before the experiment. For solar energy heating, the developed heating systems were connected to the second room.

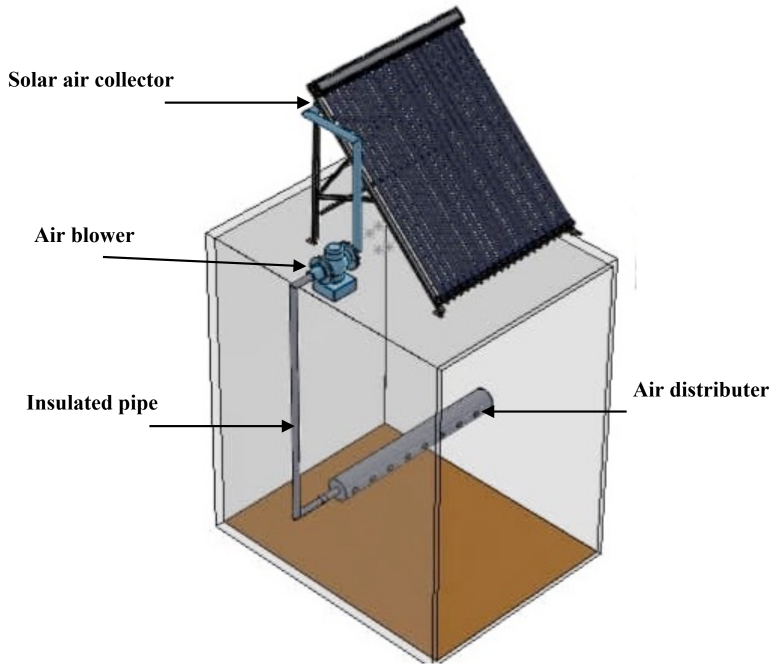

Figure (3): Solar air heating system connected to poultry house

Figure (4): Solar air heater

The water storage tank was connected to a heat exchanger installed inside the room via fixable polyethylene tubes (2.54 cm diameter). The heat exchanger was established in the room, where a group of aluminum pipes with diameter of 2.54 cm was fixed at a height of 50 cm from the room floor (above the chicks) as shown in Figure (5). Two main pipes were fixed on the room wall and connected to the exchanger. One of them was used to distribute the hot water coming from the storage tank, and another pipe was used to collect the water from the room to be returned to the storage tank again. For solar air heating system, a perforated pipe with a diameter of 5.08 cm (2 inch) was attached horizontally at a height of 1 m in the middle of the room to distribute the hot air coming from the air heater during the daytime Figure (5). The pipe was perforated with small holes in its beginning, and the diameter of the hole increases gradually as we go to the end of the pipe to ensure uniform air distribution in the whole room. Flexible polyethylene pipe with a diameter of 5.08 cm (2 inch) was used to carry the hot air from the collector on the building roof to the room. The pipe was insulated using 0.05 m thick rock wool (thermal conductivity of 0.0346 $Wm^{-1}k^{-1}$) to prevent heat loss.

Figure (5): Water heat exchanger and air distributor installed in the poultry room

4. Experimental Setup:

The experiment was conducted from 15th January to 23 February 2021, for 40 days in two identical rooms for raising broiler chicks. One room was heated by the traditional gas heating, and the other room was heated by the developed solar heating systems (SWHS for nighttime and SAHS for daytime). Figure (6) presents the daily operation procedure of the solar heating system. The solar air heating system was operated every day from 8:00 AM to 5:00 PM to heat the room. The solar water heating system was operated at the same time, but the water was circulated between the water heater and the storage tank to store solar energy (hot water). After 5:00 PM, the water cycle was closed on the solar heater and opened between the storage tank and the heat exchanger inside the room until the next morning (8 AM) and the same procedure was repeated every day during the experiment period. 50 Chicks were placed in each room, and their water and feed requirements were supplied every 8 hours throughout the day. The chicks used in the experiment were obtained from a reliable source of Arbor Acres' chicks (Authorized poultry producers in Egypt). The rooms were installed with sensors for recording the temperature and relative humidity during the experiment. The temperature inside the room with the solar heating system was observed all the time and used to control the traditional heating system. This approach was used to keep the temperature in the traditional heating room the same as the solar heating room all the time, to be able to compare the energy consumption and growing rate in both rooms. The temperature of the two rooms was controlled to provide the required temperature based on the age of the chickens. The temperature required for the poultry varied from week to week, ranging from 32°C in the first week to 26°C in the sixth week.

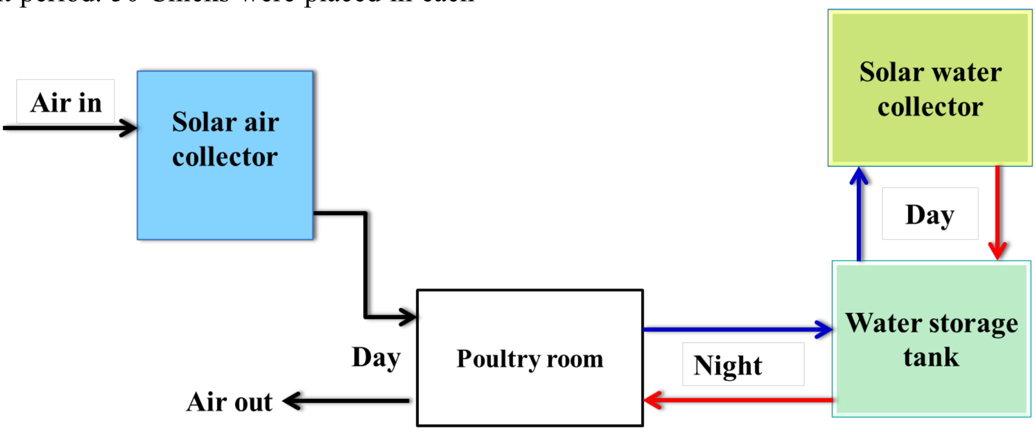

Figure (6): Daily operation procedure of the solar heating system

5. Measurements and data acquisition:

The weather conditions (solar energy, air speed, temperature, humidity, etc.) were recorded during the experiment using a meteorological station (Vantage Pro 2, Davis, USA). The air and water temperatures were recorded all the time during the experiment using thermocouples at different points of the experimental setup. The thermocouples were connected to two types of data loggers. The first data logger is Lab Jack logger system (Lab Jack logger, USA). The data logger was connected to a computer supported with instantaneous data acquisition software (Weather link, USA). The second data logger was Digi data logger (Digi-Sense®, US) consisting of 12 channels. The data logger connected with thermocouples (K-type -200:1200 °C ±0.5 °C). The means of 12 scans were also recorded and stored in the computer files every 5 minutes using the data logging program. The T/H Data Logger TH0165 was used to record the relative humidity in the room. With humidity measurement range from 0 to 100% with accuracy of ±2%RH.

6. Thermal efficiency of solar heaters:

The thermal performance of the solar heaters that works in non-stationary regime can be described theoretically by the balance equation as follows (Kishk *et al.*, 2019; Paraschiv *et al.*, 2014):

$$Q_u = I_0 - Q_p \qquad (1)$$

where I_0 is the solar radiation absorbed by the collector (W) and Q_p is the heat loss (W). Q_u is the useful energy gained by the water (W) and can be determined by the relationship:

$$Q_u = \dot{m}C_{p}(T_{out} - T_{in}) \qquad (2)$$

where: $\dot{m}$ is the fluid mass flow rate (kg s^{-1}), C_{p-w} is the specific heat of the fluid (J Kg^{-1} K^{-1}), T_{out} and T_{in} are the outlet and the inlet fluid temperature (K). The solar radiation absorbed by the solar heater can be given by the following equation:

$$I_0 = \eta_o \cdot I \cdot A_C \quad (3)$$

where η_o is the optical efficiency of solar collector, I is the total solar radiation incident upon the plate of the solar collector (Wm^{-2}) and A_c is the area of collector absorber (m^2). The heat loss from the collector is described by Eq. (4):

$$Q_P = U_C(T_C - T_{amb})A_C \quad (4)$$

where U_c is the solar heater overall-loss coefficient by convection ($Wm^{-2}K^{-1}$), T_c is the average temperature of the heater (K) and T_{amb} is the ambient average temperature (K). Equation (1) can be re-written using the equations (2 and 4) as:

$$\dot{m} \cdot c_{p(}T_{out} - T_{in}) = \eta_o \cdot I \cdot A_C - U_C(T_C - T_{amb})A_C \quad (5)$$

Finally, the thermal efficiency of the solar heater (η) can be calculated as **(Kurtbas & Turgut, 2006)**:

$$\eta = \frac{Qu}{I \cdot A_c} \quad (6)$$

Energy stored (Q_S) in the water tank during the daytime can be calculated as:

$$Q_s = M\ C_{pw}\ (T_s - T_b) \quad (7)$$

Where: C_{pw} is the specific heat of water (4186 J Kg^{-1} K^{-1}), M is the mass of water in storage tank (kg). T_s and T_b storage tank temperature (°C) at the end and the beginning of each day, respectively.

7. Growth rate and feed conversion rate of chicks:

The effect of microclimatic conditions of the poultry rooms on chicken growth stages was estimated. The weight of chicken was measured every week (data were continuously taken from 10 chicken in each room) using electrical balance (Bs-series, China) with an accuracy of 5g and capacity 30kg. Feed conversion rate (FCR) is usually used as overall measure of feed efficiency. According to (Jeremiah *et al.,* 2015), the FCR is calculated as the ratio between total amounts of feed consumed (*FC*) to total amount of poultry meat produced (*MP*):

$$FCR = \frac{FC\ (kg)}{MP\ (kg)} \quad (8)$$

8. Cost analysis:

The total cost (*TC*) assessment for the components of the operating systems was calculated according to Liu et al. (2010) as:

$$\text{TC} = \text{TFC} + \text{TVC} \quad (9)$$

where: *TFC* is the total fixed cost ($) and *TVC* is the total variable cost ($). The production cost (*PC*) was estimated by $/kg as:

$$\text{PC} = \text{TC} / \text{Poultry production} \quad (10)$$

RESULTS AND DISCUSSIONS

In this study, two identical poultry rooms were prepared and used for poultry production under two different heating systems namely, traditional heating and solar heating systems. The first room was equipped with a traditional heating system (gas heaters), meanwhile the second room was heated by solar energy (solar water and air heaters). The performance of the solar heating system was analyzed, and the results were as follows:

1. Weather conditions:

During the experiment, weather conditions such as ambient temperature (T_{amb}), relative humidity (*Rh*) and solar radiation (*SR*) were recorded by the meteorological station. All measurements were recorded per hour each day during the experiment period (6 weeks) and averaged for every week. Figure (7) presents the average conditions for the second week of the experiment. In general, during the experiment day hours (from 8 AM to 5 PM), *SR* and T_{amb} values increased gradually until they reached the maximum values at noon, and then they slowly reduced to the minimum values prior to sunset (Figure 7). Relative humidity decreased during the day hours and increased during the night and ranged from 25 to 94%. The ambient air temperature during a typical day (from 8 AM to 5 PM) of the experiment period ranged from 15 to 21°C and during the night the temperature decreased to about 10 °C as the usual temperature in Egypt during the winter (January and February) as shown in Figure (7). Therefore, the heating systems were used to provide a suitable temperature for poultry production at this time of the year. Same conditions reported during the other five weeks of experiment with little variation in ambient temperature and solar radiation.

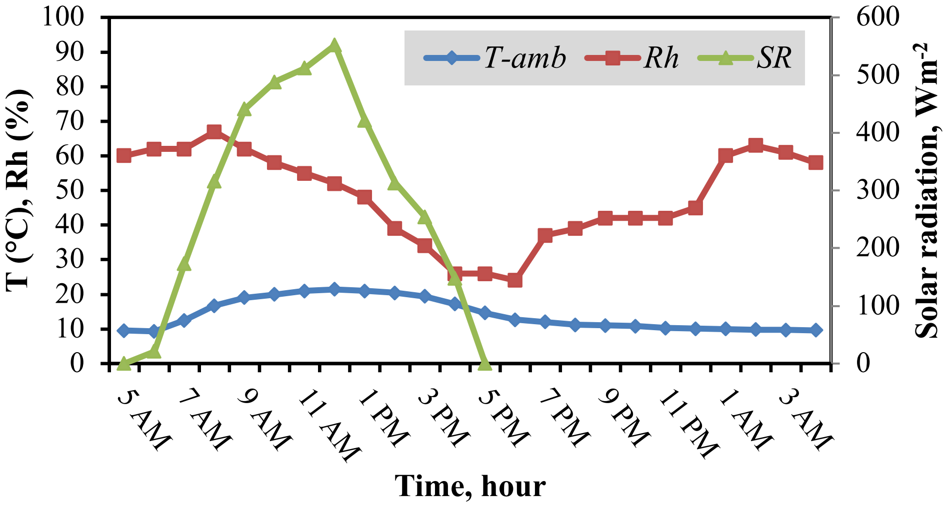

Figure (7): Average weather conditions during the second week of the experiment 22-28/1/2021

2. Performance of the solar heaters:

In the solar air heating system, the air was heated during the day in the solar heater and pumped to the poultry room to heat up the room during the day. In the solar water heating system, the water circulated during the day between the solar water heater and the storage tank. The hourly variation of the temperature of the air heated out from the solar heater ($T_{a\text{-}out}$), the temperature of water inters to the solar heater ($T_{w\text{-}in}$) and the temperature of the heated water out from the solar heater ($T_{w\text{-}out}$) were recorded and averaged during the experiment. Figure (8) shows the values of these parameters (averaged over one week) during the working day hours from 8 AM to 4 PM. The temperature of the air and water out from the solar heaters depends on the weather conditions (*SR* and T_{amb}) and on the fluid flow rate. For instance, the air and water temperatures increase with the increase of the solar radiation incident on the solar heaters. Figure (8) shows that the temperatures of the air and water out from the solar heaters ($T_{a\text{-}out}$) and ($T_{w\text{-}out}$) increased gradually with the increase of the solar radiation and the highest temperatures values for air (from 58 to 64 °C) and for water (from 58 to 60 °C) were recorded between 11:00 AM and 01:00 PM under the maximum values of *SR*. After 01:00 PM, the $T_{a\text{-}out}$ and $T_{w\text{-}out}$ decreased gradually until $T_{a\text{-}out}$ reached a temperature lower than the needed for the poultry room (22.5 °C) and the $T_{w\text{-}out}$ reached the same temperature of the inlet water ($T_{w\text{-}in}$) of about 40°C at 4 PM (prior to Sunset). It is clear that, at 4 PM, the ambient temperature and the solar radiation decreased to lower values. Therefore, at this time the solar air and water heaters were turned off, and the hot water (heated by solar water heater) will be cycled from the storage tank to the heat exchanger in the room to warm up the room during the night.

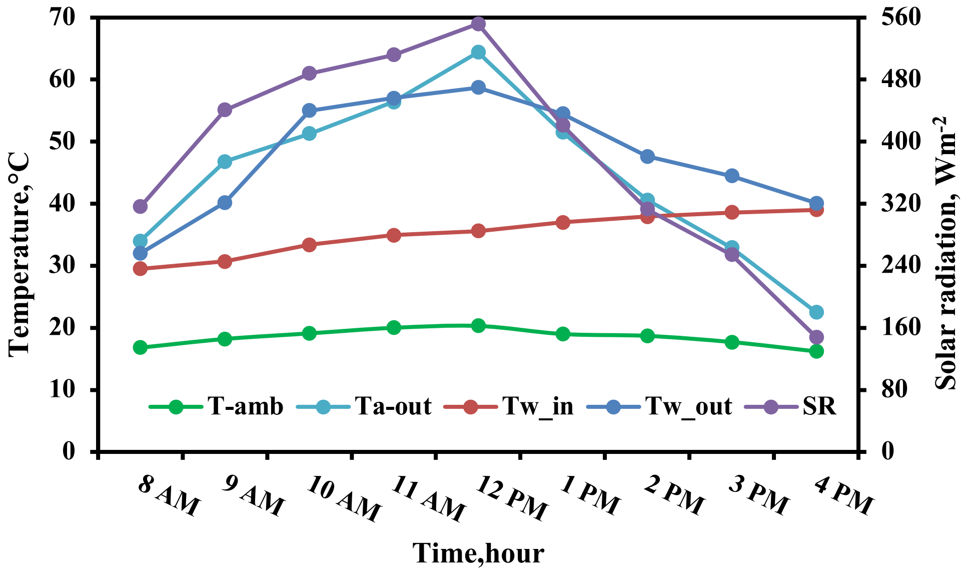

Figure (8): The average values (overall the week) of the recorded data during the work daytime.

The average values (overall the day and the week) of the recorded data during the six weeks of the experiment period were calculated and presented in Table (1). In the first week, the average ambient air temperature was 18.4 °C and this temperature was under the needed temperature of poultry checks in the first week age. So, the solar heating system was essential at this time during the day and the night. During this week, the average air temperature outside of the air heater was 44.5°C and this was enough to warm up the poultry house during the day. In the second week, we observed that there was a significant decrease in solar radiation was observed after 12 AM. due to the formation of some clouds, as the average temperature of air out from the solar heater was 45.5°C. In the third week, when the ambient air temperatures increased, the average air temperature outlet from the solar collector was 47.5°C as shown in Table (1). In the fourth week, it is noted that there was a decrease in the ambient air temperature, as the average temperature during the day of 46.4°C.

From Table (1), it is observed that in the fifth week, there was a substantial decrease in the average solar radiation and ambient temperature with average values of 377.6 (W.m^{-2}) and 14.1°C, respectively. Accordingly, the average temperature of air out from the solar heater decreased and showed lowest value of 41.9 °C compared with other weeks due to the decrease in the ambient air temperature and the presence of winds that affected the solar collector. In the sixth week, there was an improvement in the weather conditions, and the solar radiation and ambient temperature showed average values of 388.2 (W.m^{-2}) and 15.1°C, respectively. As a result, the air temperature out from the solar collector reached an average of 45.5°C during the day Table (1).

Table (1): The average values for solar radiation (*SR*), ambient temperature (T_{amb}) and temperature of heated air ($T_{a\text{-}out}$). temperature of water out from the heater ($T_{w\text{-}out}$) and temperature of water in the storage tank at the Sunset time of 4 PM ($T_{w\text{-}in}$)

	SR **(W.m^{-2})**	**T_{amb} (°C)**	**$T_{a\text{-}out}$ (°C)**	**$T_{w\text{-}out}$ (°C)**	**$T_{w\text{-}in}$ (°C)**
W1	382.2	18.4	44.5	47.7	39.0
W2	382.9	19.6	45.5	47.0	38.8
W3	388.7	21.0	47.5	48.1	41.8
W4	385.1	20.7	46.4	48.1	40.1
W5	377.6	14.1	41.9	48.5	39.0
W6	388.2	15.1	45.5	48.2	40.3

Depending on the weather conditions, the values of the average water temperatures heated in the solar heater ranged from 47.0 °C to 48.5 °C during the experiment period. The water temperature in the storage tank at the end of day (4 PM) ranged from 38.8 °C to 41.8 °C during the experiment period. This hot water circulated in the poultry room after 4 PM (when the solar heaters closed for air and water) and during the night to keep the room temperature as high as possible to meet the temperature requirements for the chicks. From Table (1), it can be noted that the performance of the solar water heater was almost stable during the six weeks of the experiment, and the temperature was a little difference between the weeks during the experiment. For instance, in the second week, a decrease is observed in the average temperatures of the water out from the heater to be 47.0 °C and resulted in a final temperature of the water in the storage tank to be 38.8 °C. These minimum values are recorded due to the weather conditions this week with low ambient temperature and solar radiation. On the contrary, in the third week, there was an increase in solar radiation and ambient air temperature, and this resulted in higher water temperature in the storage tank to be 41.8 °C. The energy stored in the water during each day of the experiment was calculated using equation (7) and presented in Table (2). In general, the energy stored in the water tank changed from day to day and from week to week based on the weather conditions. For instance, the energy stored in water increased with the increase of solar radiation, similar to the thermal efficiency and as a result, the highest stored energy was reported in the fourth week of 66.5 MJ and the lowest value of stored energy was reported in the fifth week of 61.9 MJ as shown in Table (2).

Table 2: Energy stored in the water tank (MJ) during each day of the experiment

Day	Week					
	w1	**w2**	**w3**	**w4**	**w5**	**w6**
1	11.1	8.5	9.4	10.0	8.0	8.8
2	9.8	9.1	9.5	9.1	9.6	9.1
3	8.4	10.1	9.8	9.6	8.4	10.1
4	8.7	9.3	9.5	9.5	9.5	9.1
5	7.7	8.6	9.3	9.8	10.3	8.9
6	8.3	9.4	9.5	9.2	7.5	9.5
7	10.1	8.6	8.8	9.3	8.6	8.6
Total per week	**64.1**	**63.6**	**65.8**	**66.5**	**61.9**	**64.1**
Total period	**386.0** (MJ)					

3. Thermal efficiency of solar heaters:

One of the most important parameters to evaluate the performance of the system is the thermal efficiency of the solar heater. The temperature difference between the inlet and outlet air and water to and from the solar heaters (ΔT_a and ΔT_w) during the experiment were calculated and used to determine the thermal efficiency of the solar heaters (η_a and η_w) according to equation (6) and the results presented in Figure (9). In general, ΔT values increased to maximum values at the noon and then decreased during the evening hours. The temperature differences between inlet and outlet air and water were higher at the higher solar radiation and reached higher values at noon hours of about 44.1 °C and 23.1°C for air and water, respectively. These results are in agreement with that reported by Bolaji (2006). The thermal efficiency of the developed solar heaters (η_a and η_w) is shown in Figure (9). At the morning and afternoon hours, the thermal efficiency recorded low values due to the lower solar intensity at these times. However, at noon, the solar heaters recorded higher values of thermal efficiency of 63.6% and 72.9% for air and water heaters, respectively.

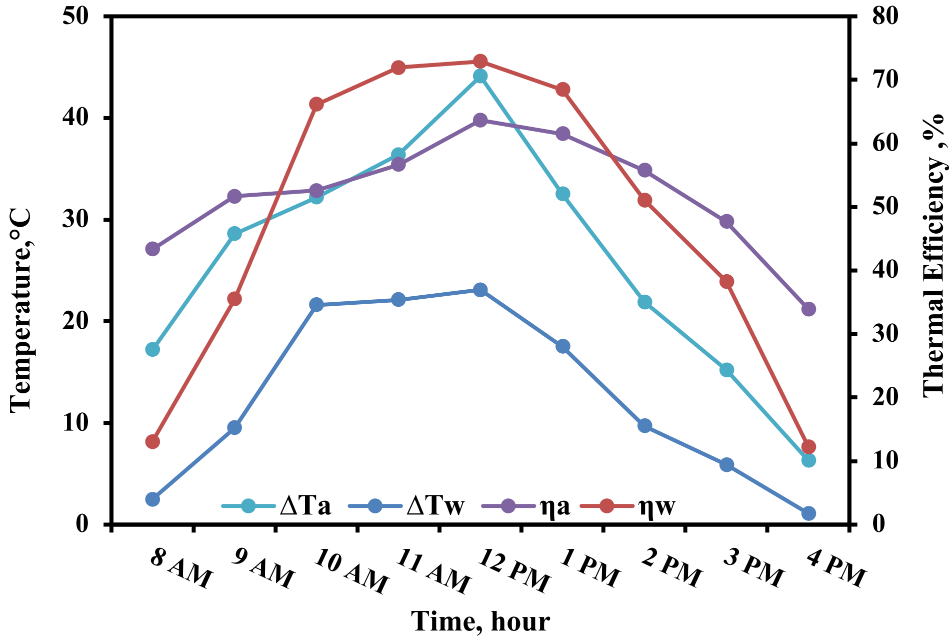

Figure (9): Average temperature differences and thermal efficiency of solar heaters during the experiment period.

Table (3) presents the weekly average temperature difference and thermal efficiency of the solar heaters during the experiment period. The solar air heater was able to raise the air temperature (ΔT_a) with an average of 25.8 °C, with an overall average thermal efficiency (η_a) of 52.6 % at a constant operational air flow rate of 1.55 kg min^{-1}. The solar water heater was able to raise the water temperature (ΔT_w) with an average of 12.5 °C, resulting in an average overall thermal efficiency of 52.1 % at water flow rate of 0.6 kg min^{-1} as shown in Table (3). It should be noted here that both solar heaters reported the same values of thermal efficiency despite the air heater rising the air temperature with a double rate higher than the water heater. This is because the air flow rate (1.55 kg min^{-1}) was also almost double the water flow rate (0.6 kg min^{-1}). The performance of the solar heaters was almost stable during the six weeks of experiment as shown in Table (3). For the air heater, the values of ΔT_a ranged from 24.7 to 26.4 °C and the average thermal efficiency (η_a) ranged from 51.1% to 53.7%. For the water heater, the values of ΔT_w ranged from 12.1 °C to 12.9 °C and the average thermal efficiency (η_w) ranged from 50.5% to 53.5 %. The results of the solar air heater agree with Kishk et al. (2019) who reported ΔT_a values ranged from 19 to 22 in October. Moreover, the obtained thermal efficiency (η_a) in agreement with the values reported by ElGamal et al. (2021), as the thermal efficiency was found to be 50.9 in July.

Table 3. The weekly average temperature difference and thermal efficiency of the solar heaters

Week (w)	ΔT_a (°C)	η_a (%)	ΔT_w (°C)	η_w (%)
1	26.0	51.8	12.6	52.1
2	25.8	53.4	12.2	52.0
3	26.4	53.7	12.1	51.6
4	25.7	52.5	12.6	53.5
5	24.7	51.1	12.3	50.5
6	26.1	52.8	12.9	52.6
Average	**25.8**	**52.6**	**12.5**	**52.1**

4. Poultry room temperature:

As two identical rooms was used for raising broiler chicks. One room was heated by the traditional gas heating, and the other room was heated by the developed solar heating systems (SAHS for daytime and SWHS for nighttime). The temperature inside the room with the solar heating system was observed all the time and used to control the traditional heating system. This approach was used to keep the temperature in the traditional heating room the same as the solar heating room all the time, to be able to compare the energy consumption and growing rate in both rooms. The temperature of the two rooms was controlled to provide the required temperature based on the age of the chickens. Figure (10) presents the temperature of the solar heated room (T_{r-s}) and the traditional (gas) heated room (T_{r-t}) for 24 hours compared to the ambient temperature (T_{amb}) outside the rooms. The temperatures of the two rooms were close to the required temperature for poultry production during the experiment, and ranged from 28 °C to 30 °C while the average ambient air temperature was 15 °C. The rooms' temperatures remained stable in the needed temperature range during the 24 hour per day by controlling the heating systems. Table (4) presents the average temperature maintained in the room during the six weeks of the experiment. The room temperature decreased week by week as the checks grew up. For instance, in the first two weeks the rooms' temperature maintained in the range of 31±1 °C, and for next two weeks in the range of 29±1 °C, and for the last two weeks the temperature in the range of 27±1 °C as shown in Table (4). Based on the temperature difference between the ambient air and the room temperature, the heating energy achieved by the solar heating system (Qs) was calculated as presented in Table (4). The energy changed from week to week and ranged from 33.0 to 52.2 MJ per week. The total heating energy for the room during the whole experiment period was 238.1 MJ.

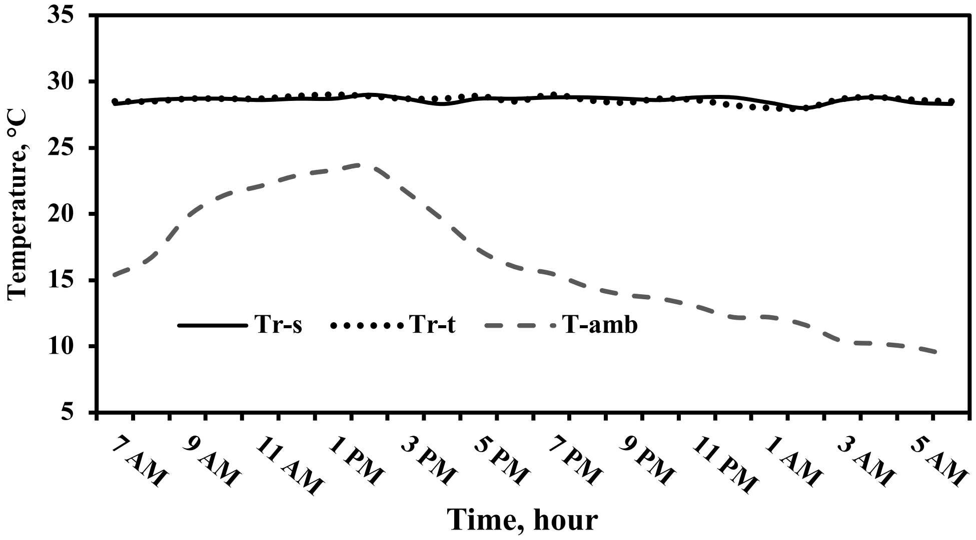

Figure (10): Average temperatures of the traditional heating room and the solar heating room and ambient air.

Table (4): Heating energy achieved by the solar system during the experiment period

Week	Tr-s (°C)	T_{amb} (°C)	∆Tr (°C)	*Qs* (MJ/week)
1	32.5	14.1	18.4	48.5
2	31.4	11.6	19.8	52.2
3	29.7	16.8	12.9	34.0
4	28.6	16.1	12.5	33.0
5	27.6	14.7	12.9	34.0
6	26.7	12.9	13.8	36.4
	Total			**238.1(MJ)**

5. Relative humidity in poultry rooms:

Relative humidity was recorded inside the poultry rooms heated by both heating systems for 24 hours and presented in Figure (11) for a typical day in the first week. It is clear that, the use of air heated by the solar heater has helped increase the efficiency of the ventilation process and reduce humidity inside the room. The air in the room was continuously changed while maintaining constant temperatures, which is difficult to do when using traditional heating systems. The relative humidity in the room heated by solar air energy maintained under 45%. Meanwhile, the relative humidity in room heated by traditional gas heating was higher than 58% during the day as seen in Figure (11). High humidity causes high thermal stress to poultry and affects the quality of the floor bedding and thus increases the chances of contracting intestinal and respiratory diseases, which leads to a decrease in the production quantity of poultry and increases their mortality rate. These results are agreement with Costantino et al. (2016).

6. Feed conversion rate:

The conversion rate (FCR) of poultry in the room heated by solar energy was lower than the FCR of poultry in the other room which is heated by traditional heating systems as shown in Figure (12). For instance, during the first week, the chicks weigh was 7 g higher in the solar energy room (186 g) than the traditional room (179 g) at the same feeding rate. This difference increased as the chicks grew until reached 134 g in the last week. In other words, the room heated by the solar system produced poultry meat more than the room heated by traditional system by a rate of 134 g for each bird which resulted in an increase in the production by about 6.7 kg meat (for 50 birds) at the same feeding rate.

7. Poultry production cost:

The cost analysis of the poultry production in the two rooms heated by traditional and solar systems are presented in Table (5). The cost analysis revealed that the use of solar energy for heating reduces the costs of heating operations in the winter and affects the weather conditions inside the room. From Table (5), it can be concluded that firstly, the production costs were lower in solar heating than in traditional heating, as the feeding was the same in each of the two rooms. Secondly, the costs of medicine are lower in solar heating than in traditional heating. This is due to the use of hot air, which helps to heat and ventilate at the same time, thus reducing respiratory and intestinal diseases. Thirdly, the costs of solar heating were lower than traditional heating. Therefore, with the high productivity and lower operational costs of the solar heating room, the profits in the solar heating room were higher than in the traditional heating room.

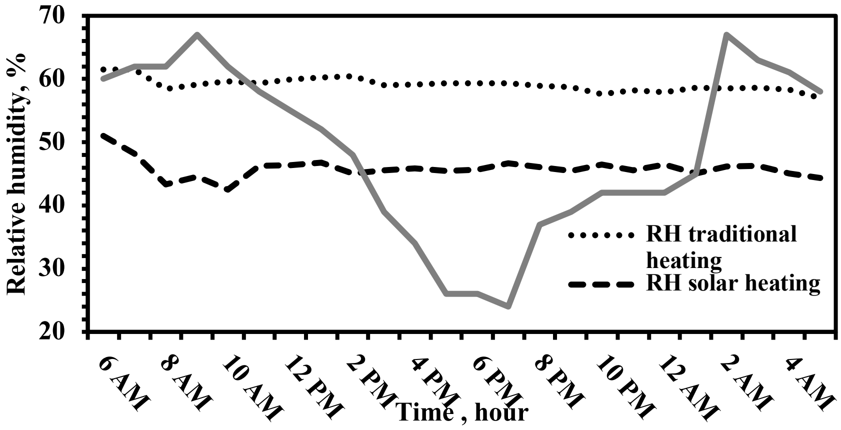

Figure (11): Comparison of the relative humidity of both the experimental room and the control room during one day of the experiment

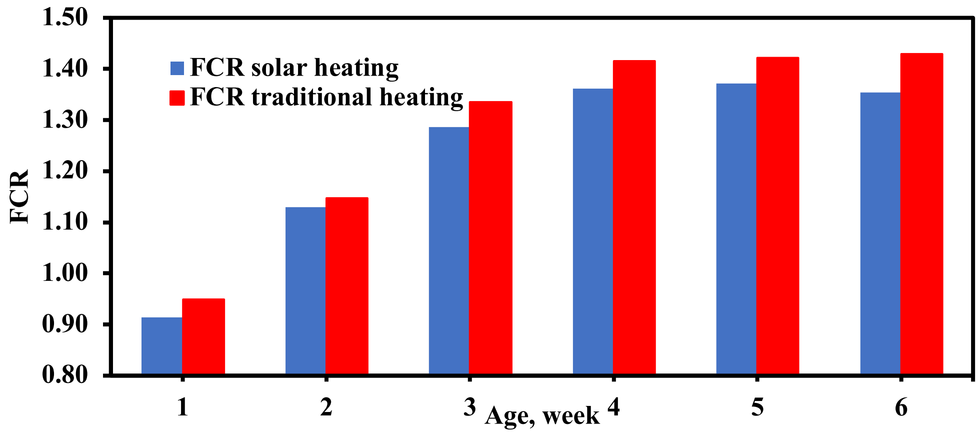

Figure (12): Comparison of feed conversion rate for traditional heating and solar heating

Table 5: Production costs (US dollars, $) of the two heating systems used for poultry rooms ($=15.8LE in the year 2021).

Item	Solar heating cost (US dollars, $)	Traditional heating (US dollars, $)
Feed costs (50 b)	72	72
Birds (50)	6.3	6.3
Treatment costs	4.75	6
Heating costs	12.7 (heater + w pump)	19.75 (gas cy)
Other costs	6.3	6.3
Total costs	**102.05**	**110.35**
Total sales	196.2	178.3
Net profit	**94.15**	**67.95**

CONCLLUSION

Solar heating system was developed and used for poultry room heating. The thermal performance of the developed solar heating systems was analyzed, and the results can be concluded as follows:

- The solar air and water heaters showed overall average thermal efficiency of 52.6% and 52.1%, respectively, during the six weeks of the experiment.
- The water heater was able store the energy in the water during the daytime with a rate of 64.3 MJ/week with a total of 386 MJ during the whole experiment period.
- The room heated by solar energy showed lower relative humidity to be under 45% during the day. Meanwhile, the room heated by traditional gas heating recorded higher values of *Rh* than 58% during the day. Giving a good health conditions of the chicks in the room heated by solar energy.
- The chicks in the room heated by solar energy showed conversion rate of 1.35 compared to traditional heating room of 1.43. Giving higher meat production of the room heated by solar energy at the same feeding rate.
- The production costs were lower in solar heating than in traditional heating. Therefore, with the high productivity and lower operational costs of the solar heating room, the profits in the solar heating room were higher than in the traditional heating room.

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تطوير نظام شمسي لتدفئة مزارع الدواجن

مصطفى السيد ، سامح كشك ، جمال المصرى ، رمضان الجمل
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المستخلص : هدفت هذه الدراسة إلى دراسة كفاءة الطاقة الشمسية في تدفئة غرف الدواجن مقارنةً بأنظمة التدفئة التقليدية. تم تجهيز غرفتين متطابقتين واستخدامهما لتربية دجاج التسمين لمدة 40 يوماً. تم تسخين الغرفة الأولى بالتدفئة التقليدية (الغاز) وتم تسخين الغرفة الأخرى بأنظمة التدفئة الشمسية المطورة. تم استخدام نظام تسخين الهواء الشمسي لتدفئة الغرفة خلال النهار. تم استخدام نظام تسخين المياه بالطاقة الشمسية لتسخين الماء في خزان التخزين خلال النهار. ثم يتم تدوير الماء الساخن بين خزان التخزين والمبادل الحراري داخل الغرفة خلال الليل. تم وضع 50 كتكوتاً في كل غرفة. تم تسجيل جميع البيانات المطلوبة أثناء التجربة، وتم تحليل الأداء الحراري لأنظمة التدفئة الشمسية المطورة. كشفت النتائج أن الطاقة المتجددة تتمتع بكفاءة عالية في تدفئة غرف الدواجن. كان متوسط الكفاءة الحرارية الكلية لسخانات الهواء والماء الشمسية 52.6٪ و52.1٪ على التوالي. بلغ إجمالي كمية الطاقة المخزنة في الماء أثناء التجربة 386 ميجا جول. كانت الرطوبة النسبية في الغرفة المُسخّنة بالطاقة الشمسية أقل من 45%، مقارنةً بـ 58% في غرفة التدفئة التقليدية. وبلغ معدل التحويل في غرف التدفئة الشمسية 1.35، مقارنةً بغرف التدفئة التقليدية التي بلغت 1.43.

الكلمات الدالة: حظيرة الدواجن؛ الطاقة المتجددة؛ التدفئة؛ السخانات الشمسية؛ معدل التحويل