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Assessment of a low-cost solar water heating systems in farrowing facilities

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Abstract. The objective of this study was to develop a prototype solar heater using alternative materials and then to compare its thermal efficiency against that of two other commercial solar heating systems when heating the floor of piglet housing. To evaluate the thermal heaters, temperature sensors were installed in the inlet and outlet of each floor and the thermal reservoir. The results showed good performance, however the thermal efficiency of the alternative heater was lower than the conventional systems. However, due to the construction of this solar collector with alternative materials its cost was relatively low and its operation is easier than the other conventional heater, therefore this heater is a good alternative to use for small livestock producer.

Key words: swine, solar energy, reusable materials, prototype.

INTRODUCTION

Pig farming is an activity that requires a lot of dedication from the breeder to achieve good productivity levels and, consequently, satisfactory economic results. External environmental factors and the microclimate inside the pig houses have direct and indirect effects on pig production, with temperatures outside the zone of thermal comfort leading to reduced productivity, with consequent economic damage to the operation (Pandorfi et al., 2015).

The productive and reproductive performance of pigs depends on the management system employed, which involves the system chosen for breeding, nutrition, health and facilities. These facilities, which require the larger part of initial fixed investment, are built on the basis of cost and management efficiency, with the comfort of the animal sometimes being neglected (Tolon & Nääs, 2005).

In the case of the maternity stage, this problem is heightened by the co-existence within it of two categories with very different environmental requirements. On the one hand there is the sow which must be cooled, and on the other hand, piglets, which must be heated. The range of temperatures for thermal comfort of the piglets during the first days of life is between 32 and 34 °C, whereas for the mother the within the band of 16 to 21 °C (Renaudeauet al., 2003; Johnson et al., 2009). Thus, to uphold good animal welfare by maintaining both the piglets and sows in thermal comfort presents the producer with a major problem. He is required, in a small physical space, to provide two different microenvironments or otherwise the performance of both the pigs and the piglets will be compromised (Pandorfi et al., 2005, Morello et al., 2018).

In general, the supplemental heating of piglets in maternity and nursery phase requires significant energy on the farm. Thus, there is a need for further research to minimize consumption without harming animal welfare or damaging the environment.

Alternative solar heating systems have started to be implemented in agricultural, greenhouse and animal facilities over the last few years, with the objective to save energy consumption Aiming at the possibility of replacing conventional systems with alternative systems, some prototypes of low-cost systems solar heating have been developed and studied. Studies show that rather than conductors, non-conductive alternative materials may well be used in solar heater operation (Kudish et al., 2002).

Several researchers have been working in the search for methodologies used in heating farrowing shed floors for piglets, seeking greater energy efficiency, welfare and productive performance of these animals (Kudish et al., 2002; Silva et al., 2005; Sarubbi et al., 2010; Fernandes et al., 2011; Seok Mun et al., 2015; Tamvakidis et al., 2015). This work will consider solar-energy as a water heating alternative, as this could have great applicability in agriculture and could be used to heat farrowing areas in the maternity on a pig farm.

The objective of this study was to evaluate the thermal efficiency and economic characteristics of an alternative solar heater prototype by comparing it with two other commercial solar heaters in order to determinate the feasibility of use of this kind the heaters for small livestock producers. The application of the systems is in the heat of thermal floors usually present inside farrowing shelters for piglets.

MATERIALS AND METHODS

Construction and installation of solar collectors

The entire study was conducted at the Federal University of Lavras, in the gantry of the Department of Engineering, latitude 21° 14” S longitude 45° 00” W and altitude 920 m, with climate, according to the Köppen classification, classified as Cwa (humid temperate with dry winter and rainy summer).

For this, we built a solar water heater prototype using alternative materials (ASWH) and compared it with a conventional solar water heater (CSWH).

The conventional solar water heater 1 (CSWH1) had a solar collector plate of PVC, painted matt black, and a thermal reservoir fabricated from high density polyethylene and coated with thermal interface material.

The conventional solar water heater 2 (CSWH2) had a solar collector of glass plate, made of extruded aluminum, with internal fins painted in matte black to absorb radiation and transfer it to internal piping. The thermal reservoir had components of internal cylinder, pipes manufactured with stainless steel, and rigid expanded polyurethane. More details can be seen in Fig. 1.

The prototype of solar water heaters manufactured with alternative materials (ASWH) was built with PVC pipes and connections (1/2” diameter), PET bottles and milk cartons (Tetra Pak®). In this prototype, the PET bottles were intended to protect the interior of the collector from external interference, such as winds and changes in air temperature. 60 bottles of polyethylene terephthalate (PET) transparent 2 liters were used. For this the cap and bottom of each bottle were removed. Tetra Pak® boxes were opened at the top and bottom, leaving them flattened. To maintain the standard in all the boxes, a cutting jig was used. The thermal properties of these material are show in the Table 1 (Scheirs et al., 2003).

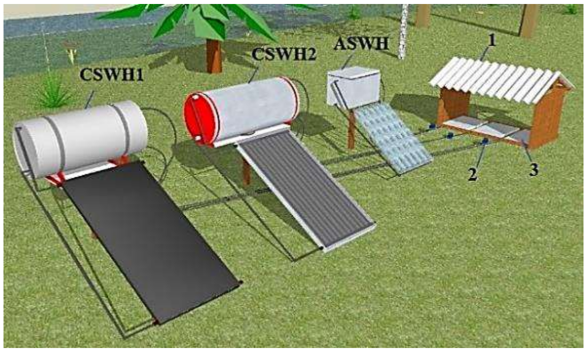


Figure 1. Assembly diagram of conventional solar heaters (CSWH1 and CSWH2) and alternative (ASWH). Legend: 1 – Protective Shelter; 2 – Water pump; and 3 – Heated cement floor.

Table 1. Average efficiency of thermal reservoirs tested in this study

Thermal Properties	PET bottles	Milk cartons
Specific heat J K^{-1} kg^{-1}	1,200–1,350	1,340–1,400
Thermal conductivity W m^{-1} K^{-1}	0.15–0.40	0.078–0.760

They were then folded in order to take advantage of the side creases of the package and two cuts were made on top, diagonally, to make it possible to fit the internal curvature of the PET bottle, also giving support to the box, and keeping it straight and in contact with the PVC pipe. Tetra Pak® boxes were painted matte black to absorb heat which is retained within the bottles to then be transferred to the water through the PVC pipes which were also painted matte black. In the ASWH assembly process, we used 10 columns with PVC pipes for hot water with 6 bottles in each column, the last bottle, cut just below the upper nozzle (Fig. 2, a).

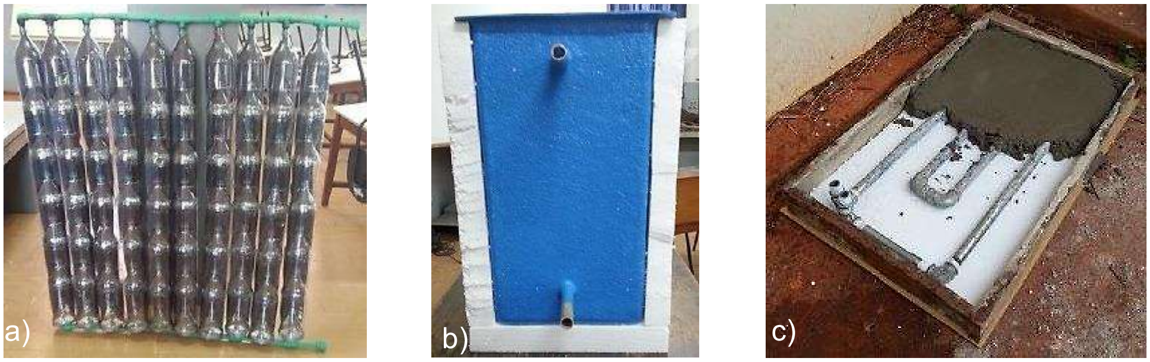


Figure 2. (a) Alternative solar heater prototype mounted and (b) the process of building alternative hot water tank, and (c) cement floors.

In an alternative construction of the hot water reservoir, a 50 liter fiberglass water tank was used, covered with polystyrene plates (3.0 cm) Silver Tape and a self-adhesive asphalt and aluminum blanket (0.25 cm) to protect the Polystyrene boards from the weather (Fig. 2, b). Four 20 mm holes were made in the reservoir, two holes being for circulation of water from the thermal reservoir to the solar collector and the other two holes for water circulation from the heat reservoir to the floor.

To test the three water heating systems three concrete floors (1:3 mix) have been built in the dimensions of 74.0 cm long, 46.0 cm wide by 7.0 cm high (Fig. 2, c). The floors were based on the same design characteristics used on floors present in a pig maternity. To reduce the heat dissipation at the base of the floors, we used 30 mm polystyrene boards. A 20 mm galvanized steel pipe was placed on each floor, forming a coil, to evenly distribute heat from the water inside the floor. The floors were left in places with shade and covered with plastic sheeting, and were daily moistened to prevent cracks.

Instrumentation and data collection

To test and evaluate the heating efficiency of the two water heating systems four thermocouple sensors (K type, precision ± 1.0 °C) with digital display were used in each system, being allocated to the entrance and exit of the heat tank and to the entrance and exit of the floor. The floors were placed inside a wooden shed with fibro-cement tile cover to prevent direct incidence of solar radiation on the floor surface. We used a small low-flow water pump (mod. ZC-T40, voltage 12 V and 1.05 A) in each system for recirculating hot water. To control the pump drive in each system, a digital controller was used - thermostat (Tholz® and Mod. 601 N) designed for solar heating applications, which operated to control water flow through the temperature differential between the entrance to the floor (Tep) and the thermal reservoir (Ter). So every time the gradient between Tep and Ter was higher than 5.0 °C, the water pump was activated.

Water temperature data (input - Ter and output - Tsr of the tank and input - Tep and output - Tsp of the floor, sensors 1, 2, 3 and 4, respectively), surface temperature of the floor and climatic data were collected for 10 non-consecutive days in July during the hottest time of day (9:00 to 16:00 h), the interval between collections being fifteen minutes (Fig. 3). We used an infrared laser digital thermometer (Instrutemp®, mod. ITTI 550 and precision ± 2.0 °C) for measuring the temperature of the floor surface, which were collected at nine equidistant points.

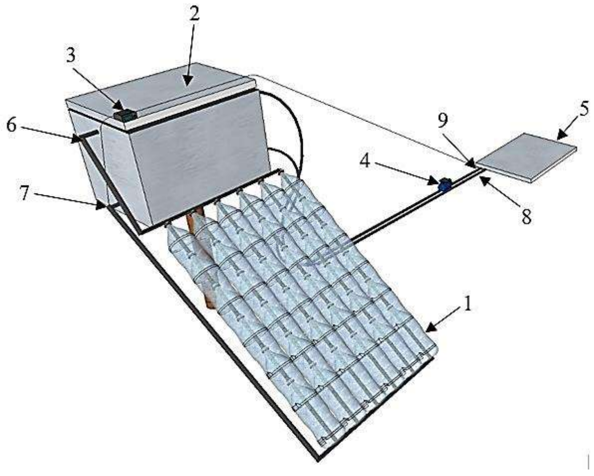


Figure 3. Scheme for installation of temperature sensors Legend: 1 – Solar Collector; 2 – Water reservoir (boiler); 3 – Controller (thermostat); 4 – Water pump; 5 – Floor; 6 – Sensor 1 (Ter); 7 – Sensor 2 (Tsr); 8 – Sensor 3 (Tep); 9 – Sensor 4 (Tsp).

Source: the authors.

Environmental climate data (air temperature, relative humidity, irradiance, wind speed, and wind direction) were collected at the meteorological station of the National Institute for Space Research (INPE) located about three hundred meters from the place of study.

Mathematical model for calculation of efficiency

With the water temperature data (input and output of the thermal reservoir and entrance and floor exit) surface temperature of the floor and climatic data from this study, we calculated the amount of heat (Q_u, kcal) required to heat a given volume of water using equation 1, as suggested by Siqueira et al. (2008) and Sprenger et al. (2007).

$$Q_u = m \cdot Cp \cdot \Delta t \qquad (1)$$

where m – volume of water to be heated (kg); C – Specific heat of water (kcal kg^{-1} °C); Δt – variation in temperature between water and environment (°C).

The heating efficiency (η) of each collector was calculated by Eq. 2 (Struckmann, 2008):

$$\eta = \frac{Q_u}{A \cdot I} \qquad (2)$$

where η – instantaneous thermal efficiency of the collector; Q_u – useful energy gain (kcal); I – intensity of solar radiation, incident on the aperture plane of the solar collector (kcal m^{-2}); A – area of the solar collector (m^2).

Experimental design and statistical analysis

The experiment was conducted following a randomized block design (RBD) with a factorial scheme of 3 x 8 (3 treatments and 8 blocks). Measurements were made for 10 days, and every day was considered as a block. Replicates were performed every 15 min for each treatment. The mean response variable inlet water temperature and output of the thermal reservoir and entrance and exit to floor, surface temperature of the floor and microenvironment climate data were compared by Tukey test ($P < 0.05$). All statistical analysis was performed using the statistical program Statistical Analysis System (SAS, 1992).

RESULTS AND DISCUSSION

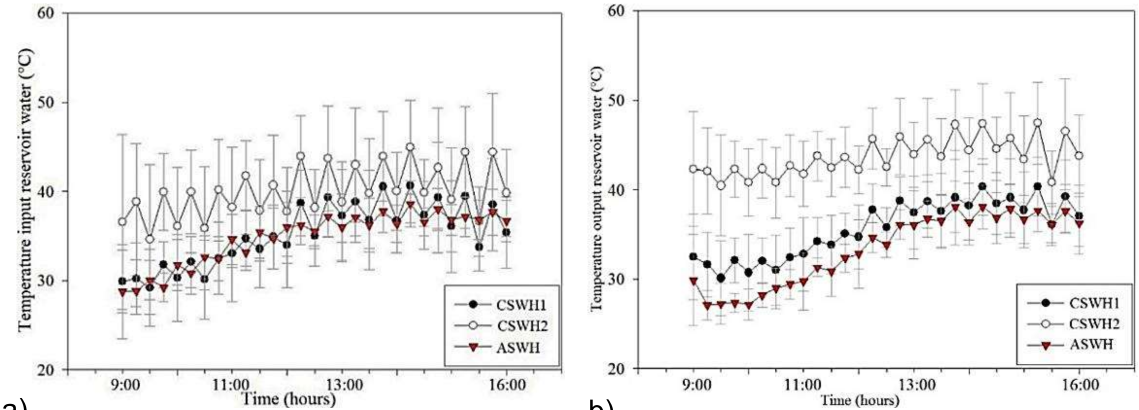
During the trial period the average air temperature remained at 21.9 ± 3.7 °C, with an average relative humidity of 60.4 ± 5.0%, solar radiation of 391.2 ± 207.8 W m^{-2} and air velocity of 1.7 ± 0.8 m s^{-1}.

Fig. 4 shows, the inlet water temperature behavior in the hottest hours of the day of (T_{er}) and outlet (T_{sr}) of the thermal reservoir. It was found that CSWH1 and ASWH systems showed no significant differences in the average values of T_{er} ($p < 0.05$, Tukey). The results show that during the day the behavior of T_{er} in these two systems is similar throughout the study period, with small variations (Fig. 4, a). The largest values of T_{er} were observed in the CSWH2 system (40.05 ± 3.2 °C), where the average value of T_{er} remained above 40 °C most of the time, and the mean variation of T_{er} in the CSWH2 system from the others was 4.8 °C.

It was found that all systems showed significant differences in the mean values of T_{er} ($p < 0.05$, Tukey). In ASWH and CSWH1 systems, there was a growing trend in values of T_{sr} which remained a stable trend between 13:00 and 15:30 (Fig. 4, b). The highest average value of T_{sr} was observed in the CSWH2 system (43.6 ± 2.6 °C), followed by CSWH1 (35.6 ± 3.7 °C) and ASWH (33.4 ± 3.5 °C).

Bortoletto et al. (2012), evaluating a solar heating system with an alternative thermal reservoir and comparing with a conventional system, found mean temperature of incoming water in the reservoir 55.9 and 81.5 °C respectively.

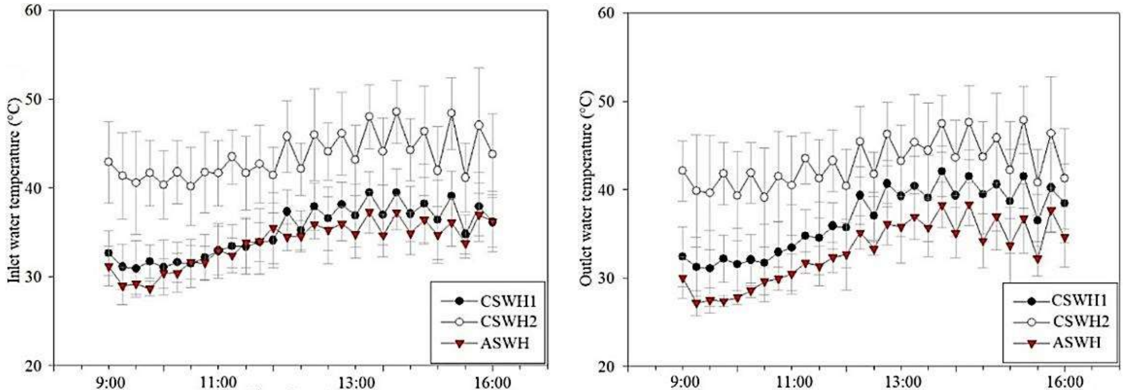
Pereira et al. (2000), evaluating a solar collector constructed of alternative materials and compared with a conventional system found mean water temperature in the reservoir of alternative and conventional systems of 35.4 °C and 45.4 °C respectively.



a) b)

Figure 4. Mean and standard deviation of temperature (a) input (T_{er}) and (b) output (T_{sr}) reservoir water (in °C) during the collection period.

Fig. 5 shows the inlet water temperature (T_{ep}) and outlet (T_{sp}) from the floor. The mean of T_{ep} in the tested treatments showed significant differences ($p > 0.05$, Tukey). In CSWH2 system, it presented higher mean values of T_{ep}, reaching values greater than 45 °C after 13:00. The system presented CSWH1 T_{ep} value slightly larger than the ASWH system. The average value of T_{ep} CSWH2 the system was 43.5 ± 2.5 °C, followed by CSWH1 systems (35.1 ± 2.8 °C) and asthma (33.8 ± 2.5 °C).



a) b)

Figure 5. Mean and standard deviation of temperature (a) input (T_{ep}) and (b) output (T_{sp}) floor (°C) during the collection period.

There was a significant difference between the mean values of T_{sp} for the evaluated systems ($p > 0.05$, Tukey). The results show a trend similar to the behavior of T_{sr} of

CSWH1 and ASWH systems during the study period, although the ASWH system presented a lower mean (33.4 ± 4.5 °C) in view of the difference of the constructive characteristics of each system. This is due to the quality of materials with low thermal insulation used in the thermal reservoir. The mean T_{sp} of the CSWH2 system had different behavior when compared to other systems evaluated in this study (Fig. 5, b).

The fluctuation in the average values of T_{er} T_{sr} T_{ep} and T_{sp} over the study period was due to the variation in the activation of the water pump by the controller (thermostat) that was activated every time the difference T_{ep} and T_{er} was greater than 5.0 °C. This difference is probably related to heat loss in the pipes leading the water from the heat reservoir to the floor, and in this case better insulation on these tubes is recommended.

The results show that early in the day, T_{er} and T_{ep} of ASWH and CSWH1 systems were close to the average values of the air temperature. Probably the thermal insulation of these systems is not sufficient to minimize heat loss during the night.

The comparison between treatments shown in Fig. 6 is the mean result of floor surface temperature (T_s) of each rated heating system. According to the results, significant differences were found between the mean T_s in all heating systems, by Tukey test, considering a nominal value of 5% probability. The mean and the standard deviation of the floor surface temperature for CSWH1, CSWH2 and ASWH systems were 33.2 ± 2.8 °C, 36.5 ± 2.7 °C and 31.4 ± 2.9 °C respectively. In general, one can say that for the thermal comfort zone for piglets in the farrowing phase, the three treatments are recommended, but it should be remembered that these data are daily averages.

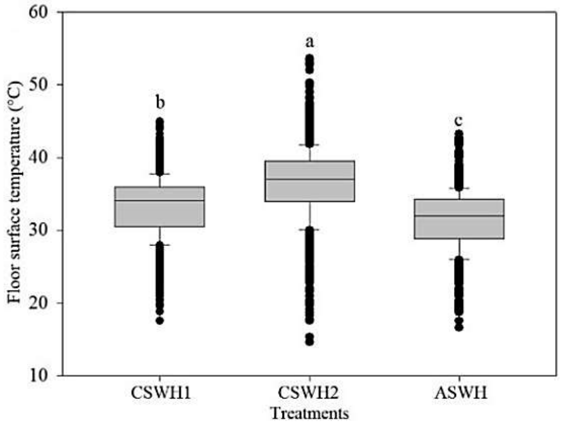


Figure 6. Analysis of variance between the temperature values of the floor surface in this study. Means followed by letter are not statistically different from each other by the Tukey test at 5% probability.

Fig. 7 illustrates the behavior of T_s in each rated heating system. Heat distributions were verified in different shades of colors on the surface of the floors in the evaluated systems. The regions at the top and bottom are regions with lower values of T_s, considered cooler, which correspond to the location in and out of the protective shelter. These regions may be cooler by air currents and by the fact that the heat does not heat those locations, due to the positioning of the water pipe being situated in the central part of the floor. The light tones correspond to the heat emitted by the pipe water in these locations. This may be an indication that, to increase the thermal efficiency of the shelter, one can recommend the use of two sources of heating.

Quiniou et al. (1999), evaluating different heating systems for pigs, states that heated farrowing sheds with underfloor heating by circulating water through a hybrid system (solar panels, biogas, LPG and electricity gas) had the highest average temperatures and the largest gain of weight of piglets, providing better thermal comfort for the piglets and higher revenues from the sale of piglets.

To keep sows and piglets in their thermal comfort zones in conventional maternities is challenging, even in thermally controlled environments due to the comfortable temperature of the sows being situated in the range of 22 °C (Sulzbach et al., 2016), while for the piglets it is within the range 29–34 °C (Lossec et al., 1998; Renaudeau, 2001; Sulzbach et al., 2016). While in sows, heat stress has adverse behavioral, and physiological productivity effects (Lossec et al., 1998; Quiniou, et al., 1999; Renaudeau, 2001; Penereiro et al., 2016; Sulzbach et al., 2016), in piglets a drop in body temperature of 2 °C to 4 °C during birth, if not provided with a source of enough heat, means a hypothermic condition may occur, reducing strength and milk intake, and eventually can mean death (Lossec et al., 1998).

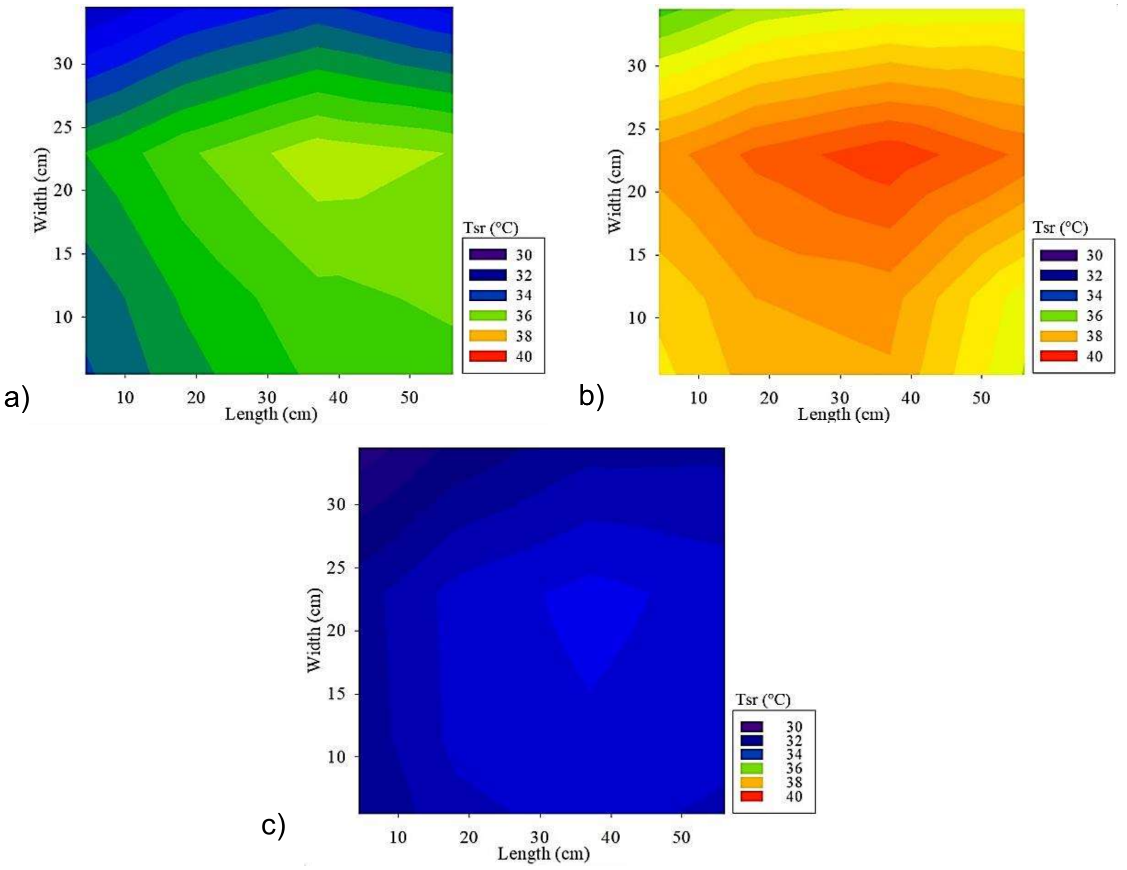


Figure 7. Mean surface temperature values (T_{sr}, °C) of the floors heated by different heating systems: a) CSWH1, b) CSWH2 and c) ASWH.

Fig. 8 shows the variation of the efficiency of the solar collectors in function during the evaluated period. It is noticed that as the solar radiation rises, the temperature gradient of inlet water temperature and outlet reservoir increases, increasing the efficiency of the collector. According to Incropera et al. (2011), this is due to the retention of heat inside these two surfaces, because the glass allows the passage of visible light waves and is opaque infrared radiation, so the radiation emitted by the absorber plate does not pass through the glass thereby increasing its temperature.

As can be observed in Fig. 8, it is possible to verify the influence caused by the wind in determining the thermal efficiency of each collector studied. As expected, the more intense winds significantly affect the ASWH and CSWH1 collector yields when compared to CSWH2. The use of the glass cover in the CSWH2 collector, which causes the accumulation of radiation emitted by the surface of the solar collector, maintaining for a longer time the thermal energy inside the pipes that exchange this energy with the water, avoiding the energy loss due to the action of the wind to the environment.

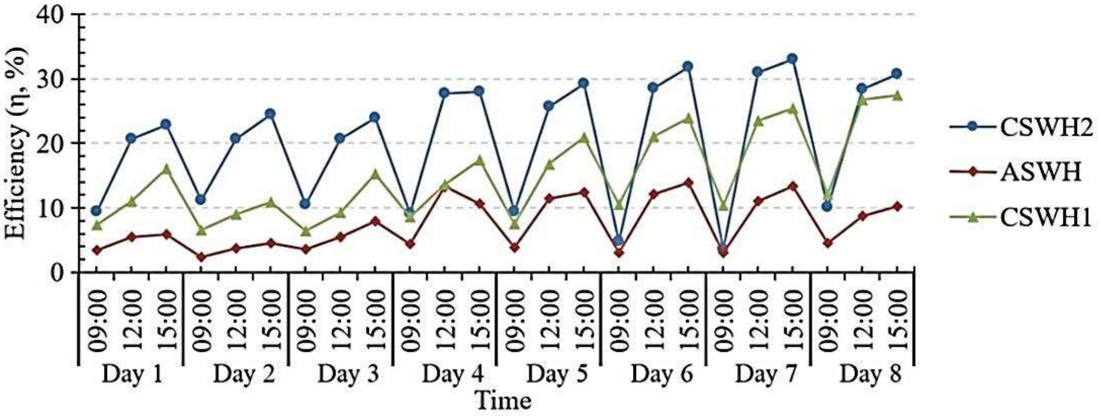


Figure 8. Efficiency of the thermal reservoirs tested during the time of study.

With the results obtained in each heating system in Table 2, where the inlet (T_{er}) and outlet (T_{sr}) water temperatures in the reservoir are explicitly listed, it is possible to find cumulative amount of heat (Q_{ac}), collector area (A_c), mean solar radiation (ΣI) and average efficiencies of each system (η) calculated by Eq. 2. According to Table 2, it can be seen that the variation between T_{er} and T_{sr} in the CSWH2 system is greater. The amount of heat (Q_{ac}) and collector area in CSWH1 and CSWH2 system are virtually equal. However, for the same amount of solar radiation (ΣI) incident in the experimental area, the CSWH2 system efficiency is higher, but when the efficiency is compared with others researchs like made by Seok Mun et al. (2015), who found The average was 64.8% and others systems as develomented by Tamvakidis et al. (2015), founded the alternative systems could have generated between 50–70% the energy that required the farrowing during the warm periods.

Table 2. Average efficiency of thermal reservoirs tested in this study

	System		
	CSWH1	CSWH2	ASWH
T_{er} (°C)	33.4	37.0	31.4
T_{sr}(°C)	36.7	43.7	33.0
Q_{ac} (Kw)	0.34	0.33	0.25
A_c (m^2)	1.73	1.70	1.30
ΣI (kW m^{-2})	0.391	0.391	0.391
η(%)	10.9	22.5	7.0
Total value (R$)	1,618.31	2,452.58	891.36

Legend: inlet water temperature (T_{er}) and outlet (T_{sr}) the reservoir, amount of accumulated heat (Q_{ac}), Collector area (A_c), the sum of mean solar radiation (ΣI) and average efficiencies of each system (η).

Probably, this greatest value in heating efficiency is due not only to the type of material used in this system, it is also due to the protective glass on the solar collector that this system has and which provides a better absorption of solar radiation, where the heat of the sun, picked up by the collector of the CSWH2 system is transferred to water circulating within its copper pipes.

As can be seen from Table 2, the ASWH system did not show good efficiency, however, when comparing the total cost of the heating efficiency of each system, we can conclude that the ASWH system is an alternative for replacing the conventional system and decreasing final cost, and the maintenance can be performed with few tools and in situ. Another alternative for increasing the heating efficiency of this system is to increase the area of the solar collector.

According Penereiro et al. (2016), assessing the heating efficiency of a solar heater constructed of alternative materials (PVC) and comparing with a conventional system (metal) mentions that thermal efficiency in the conventional metal solar heater is higher (14.4%) than that inferred in the solar heater of PVC.

CONCLUSIONS

Due to the weather conditions recorded at this stage, the solar heating systems that were more suitable in function of thermal efficiency were the conventional solar water heater with solar glass plate collector (CSWH2), followed by conventional solar water heater with solar collector of PVC (CSWH1) had the best results, follow by the solar water heater manufactured with alternative materials (ASWH).

According to the technical and economic analysis, it was verified that the lowest efficiency cost for the period studied was for the CSWH1 (US$/% 14.99) system, followed by the CSWH2 system (US$/% 27.25) and ASWH system (US$/% 31.83), respectively.

The results showed that the alternative system has a thermal efficiency lower than the conventional, however the construction of solar collectors using alternative materials stands out for its strong social and environmental nature, due to the construction cost being relatively low and the operation easy and it can be constructed and used by livestock producers for heating purposes.

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