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DESIGN AND PERFORMANCE ASSESSMENT OF A FLAT-PLATE SOLAR MILK PASTEURIZER FOR ARID PASTORAL AREAS OF KENYA

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ABSTRACT

A solar milk pasteurizer consisting of flat-plate water-heating collector and a 1.5-mm thick stainless steel cylindrical milk vat was designed and tested in an arid pastoral area of northern Kenya. The milk vat had a capacity of 80 L and a 50-mm wide hot water jacket insulated with 38-mm thick fiberglass. Hot water produced by the collector was used for pasteurizing milk. The optimum quantity of milk that could be pasteurized by this device under the study conditions was 40 L, and the average temperature difference between hot water and milk being pasteurized was 8.1 ± 1.4C. Total bacterial counts in pasteurized milk were less than 10 cfu/mL while coliform counts were negative. This low-cost solar milk pasteurizer is appropriate for arid pastoral areas without grid electricity, where milk marketing is an important income source, and where most of the milk is boiled using firewood.

PRACTICAL APPLICATIONS

Milk marketing is an important income source for people in arid areas of Kenya. To minimize losses along the marketing chain, traders boil milk using firewood, especially when transport to the market is unavailable. This places intense pressure on woody resources on the fragile environment. There is abundant supply of solar energy in the arid areas that can be harnessed using flat-plate solar collectors to provide hot water for milk processing, and thus save on the environment. The hot water produced by the solar pasteurizer could also be used for cleaning milk containers, thus improving hygiene of milk marketing. The study is expected to enhance milk marketing in arid areas, increase food security and encourage wider use of solar energy in food processing in Kenya. On a global scale, use of solar energy would reduce the rate of depletion of fossil fuels and minimize pollution arising from their use.

INTRODUCTION

Milk marketing is an important income-earning opportunity for people in the arid and semiarid lands (ASALs) of Kenya. Before milk is consumed, it should, however, be pasteurized to avoid zoonotic diseases spreading to humans. Pasteurization is a mild heat treatment applied to ensure microbial safety and to supply milk with longer shelf life. In this process, milk is heated at 72C for 15 s or 63C for 30 min (Walstra *et al*. 2006) and through this treatment, the milk, from a public health point of view, is safe for consumption. Milk traders in the Kenyan ASALs usually boil milk at collection points using firewood, which exacerbates environmental degradation on the already fragile environment. Therefore, alternative cheap and renewable energy technologies such as solar energy should be provided to small-scale farmers and traders who are involved in milk marketing. Kenya has enormous amounts of solar energy resource particularly in the ASALs, where the monthly average of global solar radiation varies from 13.3 to 30.6 $MJ/m^2/day$ (Kenya Meteorological Department, Solar radiation records 2000–2009) and, therefore, solar energy seems to be a viable alternative to firewood for heating milk in these areas.

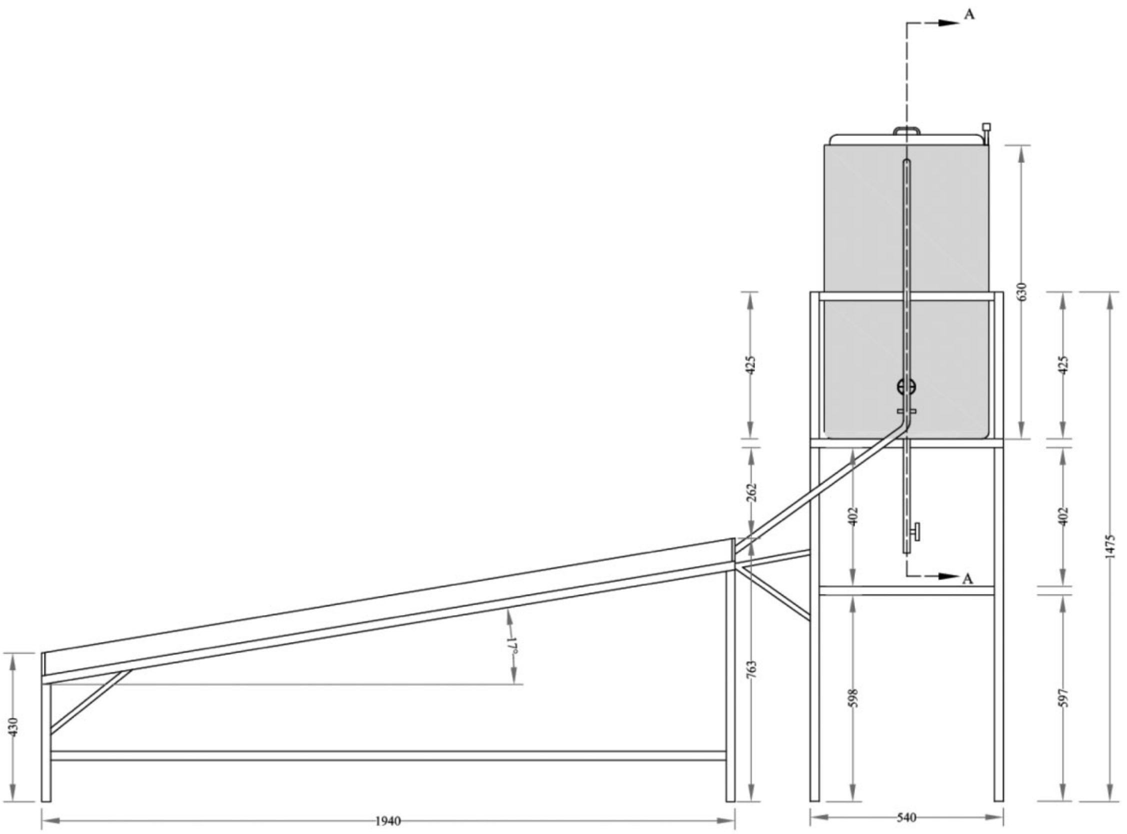

FIG. 1. SIDE VIEW OF THE SOLAR MILK PASTEURIZER (ALL FIGURES IN mm)

The use of thermosiphon solar water heating systems to provide process heat for the Kenyan food processing industry is technically feasible (Okoth 1996). These are of low cost, simple in design and fabrication, durable, and require minimal maintenance (Duffie and Beckman 2006). Therefore, there is need to extend this to the specific case for milk processing in Kenya's ASAL to minimize environmental degradation occasioned by the use of firewood to heat milk. However, no study appears to have been carried out on the use of solar energy in pasteurizing milk in Kenya. The present study, therefore, aimed at the design and testing of a low-cost flat-plate batch solar milk pasteurizer using materials readily available in the local market with the aim of enhancing milk marketing in the rural ASAL areas of Kenya.

MATERIALS AND METHODS

Design and Fabrication of the Pasteurization System

An 80-L capacity flat-plate batch solar milk pasteurizer was designed and constructed with locally available materials. The size was selected considering the daily quantities of marketed milk by traders in ASALs (20–100 L). The pasteurizing system was made up of a flat-plate water heating solar collector and milk pasteurization vat (Figs. 1 and 2). Milk was pasteurized by hot water produced by the solar collector.

Flat-plate Solar Collector. This was a commercial solar collector with gross and effective area measuring 1.82 and 1.67 m^2, respectively. The absorber was made of a copper sheet to which was soldered ten 12.7-mm nominal diameter copper tubes. The surface was treated with a selective coating (black chrome). The glazing was a special low iron glass sheet (5-mm thick) treated on the outer surface to minimize transmission of long-wave infrared radiation. The rear and side insulation were 25 and 10 mm thick fiber glass, respectively. The casing material was 24-gauge galvanized steel sheet, with a layered assembly of rubber and metallic sheet compacted by a sealing gasket. The equation of the collector efficiency (η) was:

$$\eta(\%) = 75.8 - 833.2\ (T_i - T_a)/I, \qquad (1)$$

where (T_i) is the inlet water temperature in the solar collector (C), T_a is the ambient temperature (C) and I is the insolation in plane of solar collector (W/m^2)

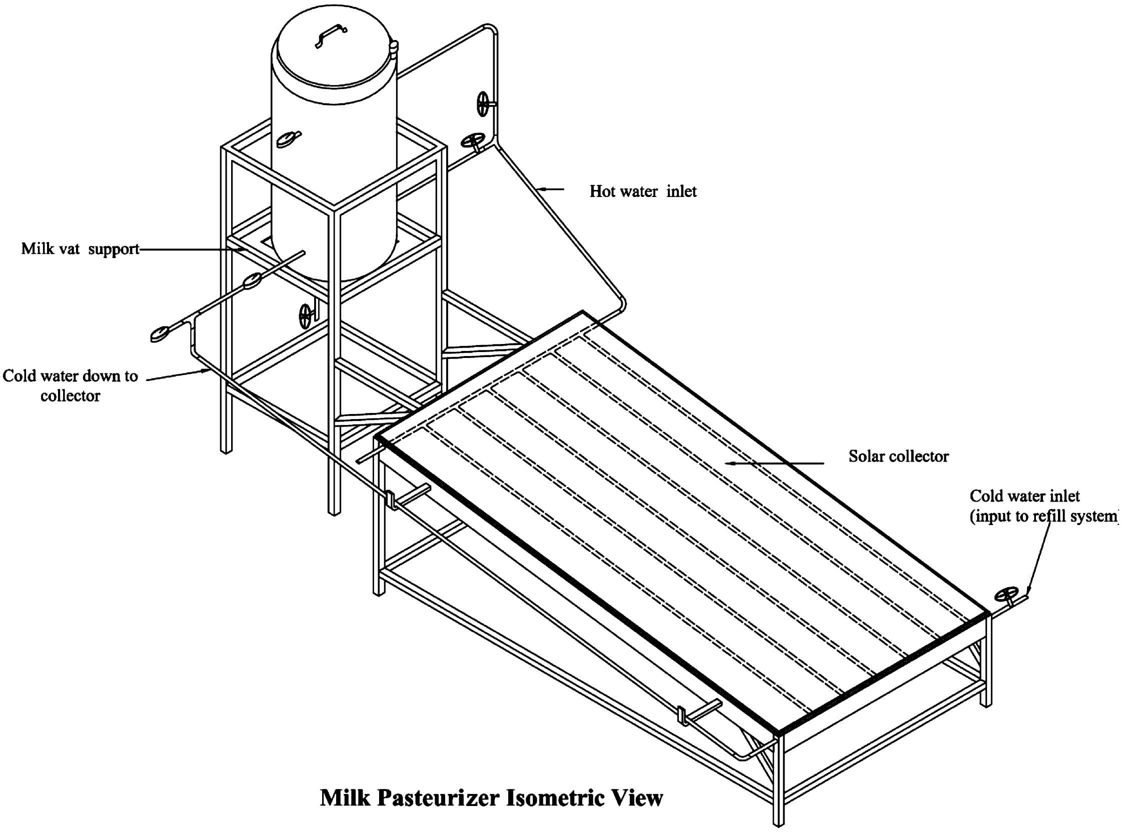

FIG. 2. ISOMETRIC VIEW OF THE SOLAR MILK PASTEURIZER SHOWING THE SOLAR COLLECTOR AND MILK CONTAINER

The solar collector was tilted at 17° from the horizontal, facing the equator. The collector absorbs solar radiation, transforms it into heat energy and conducts the heat into water flowing through the collector pipes. One pipe from the collector circulates hot water from the collector to the top of the milk vat. Another pipe from the bottom of the milk vat circulates cooler water in to the collector. These pipes were properly insulated with cotton wool to minimize heat losses.

Milk Pasteurization Vat. The milk pasteurization vat consisted of a 1.5-mm thick food grade stainless steel cylindrical tank, with a 50-mm wide hot water jacket and an outer layer of 38-mm thick fiber glass insulation (Fig. 3). It was kept on a stand such that the bottom of the tank was 0.26 m above the top of the collector. This allowed water to flow at maximum flow rate by convection from the collector through the milk vat and back (Duffie and Beckman 2006). The milk vat had a vent valve, which was open to the atmosphere to allow water inside the hot water jacket to expand while heating without a dangerous pressure build up. The water jacket held approximately 30 L of water, whereas the milk tank had a capacity of 80 L. The collector and pipings held about 20 L of water. The water jacket was directly heated by the solar collector, and in turn heated the milk to be pasteurized. The milk vat had an openable insulated lid at the top and a 12.7-mm nominal diameter stainless steel pipe at the bottom, which acted as an outlet for pasteurized milk. Valves were provided at appropriate points to operate the device.

Performance Assessment

The system was installed at the Kenya Agricultural Research Institute, National Arid Lands Research Centre, Marsabit (37.97°E, 2.32°N, altitude 1,219 m), where the average solar radiation and ambient temperature ranged from 10.9 to 28.5 MJ/m^2/day and 23 to 38C, respectively, during the study period.

Collection of Milk Samples. Camel milk samples were collected from previously selected camel herds in Marsabit. The milk samples were hygienically collected in sterile 10-L plastic jerrycans and brought to the study site within 2 h after milking. The milk was screened by clot-on-boiling test and only samples that passed the test were used. The milk was sieved using cotton cloth before pasteurization.

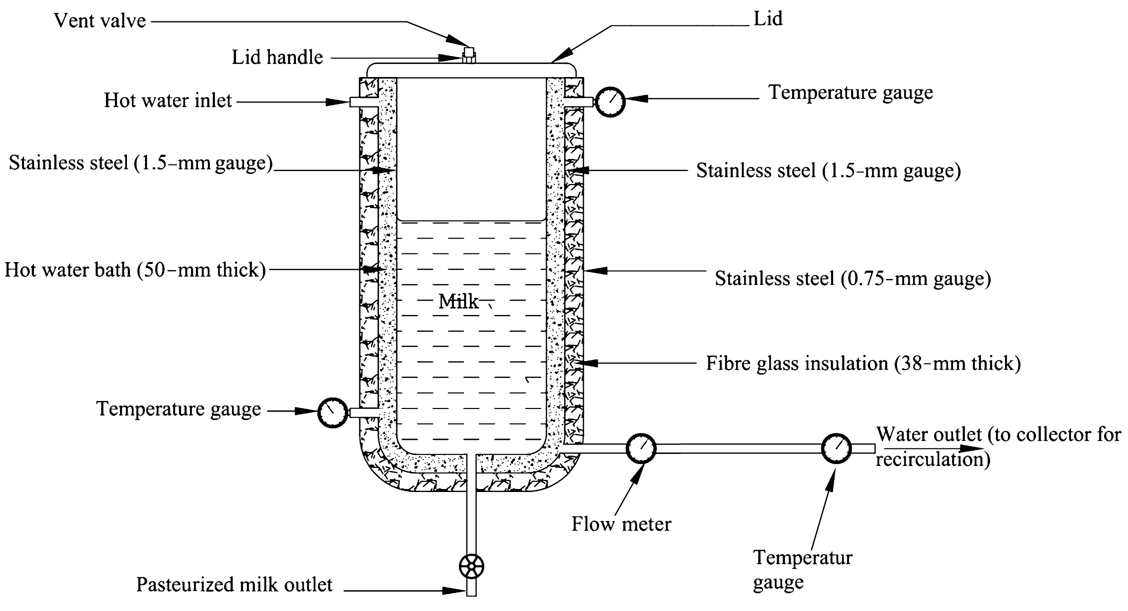

FIG. 3. CROSS-SECTION OF THE MILK PASTEURIZATION VAT

Maximum Achievable Temperatures and Optimum Volume of Milk to Be Heated. To realize the maximum achievable milk temperature and the maximum amount of milk to be heated, the quantity of milk was varied from 20 to 70 L and the setup exposed to solar radiation from 11:00 a.m. to 4:00 p.m. local time, over a period of 2 weeks.

Milk Pasteurization. The system was filled with water in the morning and milk put in the milk tank. Pasteurization was performed by thermosiphon circulation of hot water from the collector into the hot water jacket and back to the collector. As long as the sun continued to heat water in the collector, a thermosiphon circulation loop was set up whereby water flowed continuously out the bottom of the milk vat, through the collector and back into the top of the milk vat jacket. In the process, the milk was heated to pasteurization temperature by the hot water jacket. During this process, milk was stirred manually using a wooden spoon at regular intervals (approximately every 30 min). When the desired temperature was reached, the hot water flow from the collector was closed and the milk remained in this condition for 30 min (holding time) in the closed milk vat container. Experiments were conducted between 10:00 a.m. and 5:00 p.m. local time. Parameters measured included temperature of milk, T_m (C), temperature of hot water, T_w (C), water flow rate through the collector, $\dot{m}(\text{kg/s})$, ambient air temperature, T_a (C), solar radiation, I (W/m^2) and wind speed, v (m/s). Water and milk temperature were measured approximately every 30 min using digital K-Type thermocouple thermometer (type HI 9043, Hanna Instruments, Padova, Italy). Ambient temperature was measured by digital thermometer (0–60C, Model No. ETH529, Brannan Thermometers, Cleator Moor, Cumbria, England). Solar radiation data were measured by pyranometer (Kipp and Zonen, Delft, Netherlands) and wind speed by cup-and-vane anemometer, which indicated wind speed values in the range 0–30 m/s (full scale = 10 divisions; 1 division = 3 m/s). As the phosphatase test for pasteurization is not applicable for camel milk because the phosphatase enzyme is not destroyed by pasteurization (Lorenzen *et al.* 2011), adequacy of pasteurization was assured by strict time–temperature control and determination of coliforms and total bacterial counts (TBC) before and after pasteurization. TBC were determined using plate count agar (CMO325, Oxoid, Basingstoke, England) incubated at 37C for 48 h, and coliform counts using violet red bile glucose agar (CMO485, Oxoid) incubated at 37C for 24 h (APHA 1992).

Payback Calculation

Payback period of the pasteurizer was calculated by considering the equivalent savings in alternative fuels, mainly firewood, which is the main fuel used in northern Kenya (McPeak 2003), as defined in Eq. 2:

$$\text{Simple payback (in years)} = \frac{\text{initial cost}}{\text{cost saving per year}} \quad (2)$$

RESULTS AND DISCUSSION

Maximum Achievable Temperatures and Optimum Volume of Milk to Be Heated

Maximum milk temperature inversely varied with the amount of milk being heated, reaching 81.4C with 20 L, and only 41.7C when experimented with 70 L of milk (Table 1). Fourty liters was chosen as the optimum quantity of milk that could be pasteurized by this device under the study conditions (bolded in Table 1). Heating 40 L of milk to 69.7C took an average of 1.5 h, at an average insolation and ambient temperature of 783.7 W/m^2 and 30C, respectively.

Variation of temperature in the hot water jacket and in the milk container (with 40 L of milk) of the solar milk pasteurizer on a test day is shown in Table 2.

Milk Pasteurization

Figure 4 shows a temperature versus time graph for the heating process during milk pasteurization. The milk (40 L, initially at 30.2 ± 1.9C) reached the final temperature (63C) in 1.3 ± 0.5 h from the beginning of the process so it could be commercially used. Franco *et al.* (2008) reported a "come-up" time of 1.25 h during solar pasteurization of goat milk using a solar concentrator. These "come-up" times are too long when compared with other reports on milk pasteurization (Walstra *et al.* 2006). The longer "come-up" time reported in this study was due to the use of the water bath method, the volume of milk and the intensity of solar radiation in the study area. However, to shorten the pasteurization time, several collectors can be connected in series to obtain the necessary surface area to capture maximum solar radiation, or the size of the milk vat (or quantity of milk to be pasteurized) could be reduced. The temperature difference (mean ± standard deviation) between hot water and milk was 8.1 ± 1.4C. Similar results were obtained by Franco *et al.* (2008) during solar pasteurization of goat milk using a solar concentrator, who obtained a temperature difference of 10C.

TABLE 1. MAXIMUM MILK TEMPERATURE AT DIFFERENT AMOUNTS OF MILK TO BE HEATED*

Experiment Number	Volume of milk (L)	Maximum milk temperature (C)
1	20	81.4
2	30	76.0
3	**40**	**69.7**
4	50	57.6
5	60	44.2
6	70	41.7

Bold styling indicates maximum achievable temperatures and optimum volume of milk to be heated.

* Starting temperature of milk = ambient temperature (25.4 ± 2.9C).

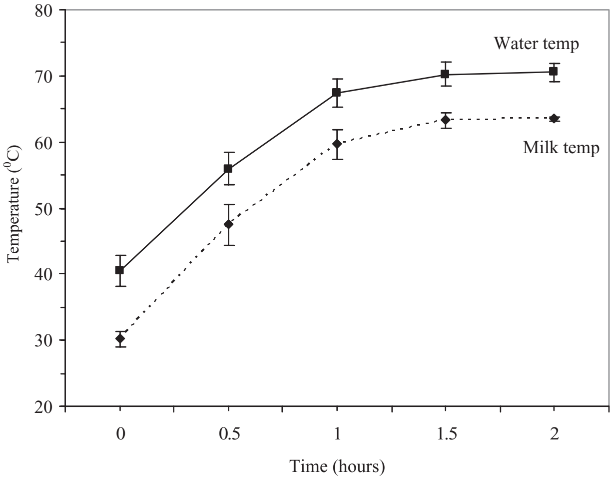

FIG. 4. AVERAGE VARIATIONS OF TEMPERATURE (TEMP) DURING SOLAR MILK PASTEURIZATION. DATA ARE MEANS OF 12 REPLICATIONS; BARS ARE STANDARD ERRORS (MILK VOLUME = 40 L)

The microbial quality of the milk before pasteurization is shown in Table 3. Following heat treatment of raw milk, TBC were reduced to less than 10 cfu/mL, while coliform counts were negative in all 12 pasteurized milk samples. This agrees with the finding of Mulwa (2009) who reported a reduction of TBC to less than 10 cfu/mL after camel milk pasteurization. However, the figure is slightly higher than the Kenya standards for pasteurized camel milk, i.e., a TBC count nil imme-

TABLE 2. VARIATION OF TEMPERATURE IN THE WATER JACKET AND MILK TANK OF THE SOLAR MILK PASTEURIZER ON A TEST DAY

Standard local time	Temp at the bottom of the water jacket, T_1 (C)	Temp at the top of the water jacket, T_2 (C)	Average temp of water $(T_1 + T_2)/2$ (C)	Temp of milk (C)	Ambient temperature (C)	Insolation (W/m^2)
10:00 a.m.	24.8	26.1	25.5	25.1	17.6	638.6
11:00 a.m.	25.1	35.5	30.3	35.4	18.6	669.2
12:00 p.m.	25.8	35.8	30.8	35.6	20.4	624.3
1:00 p.m.	37.2	40.0	38.6	48.1	22.9	800.8
2:00 p.m.	48.2	51.3	69.8	63.0	23.3	813.0
3:00 p.m.	66.7	66.8	66.8	63.2	24.4	896.7
4:00 p.m.	64.5	64.5	64.5	64.3	23.8	828.3

Temp = temperature.

TABLE 3. BACTERIAL COUNTS IN RAW CAMEL MILK

Milk sample	Total bacterial count ($\times 10^3$ cfu/mL)	Coliform count (cfu/mL)
1	3,100	<100
2	5,000	1,300
3	4,500	1,597
4	1,000	700
5	7,000	1,200
6	2,300	700
7	20,000	1,700
8	10,000	<10
9	10,000	<100
10	1,300	900
11	750	<10
12	4,800	1,600
Kenya standards*	Grade I: 0–200	0–1,000
	Grade II: 201–500	1,001–20,000

* Kenya Bureau of Standards (KEBS) (2007a).

diately after pasteurization and maximum limit 1,000 cfu/mL at end of expiry date (KEBS 2007b). Shelf life tests for pasteurized camel milk were not investigated in this study. However, Mulwa (2009) reported that pasteurized camel milk stored at 25 and 30C exceeded the KEBS (2007b) specification in less than 24 h, but stayed for 6 days at 20C.

Payback Period

According to McPeak (2003), boiling of 5 L of tea consumes about 5.5 sticks of firewood, each valued at approximately USD 0.0333, giving a total of USD 0.183. It is assumed that boiling of an equivalent amount of milk would consume the same amount of fuel. Hence, for 40 L of milk this gives USD 1.464 per day. Capital cost of the solar milk pasteurizer was USD 1,867. Assuming that the solar milk pasteurizer would be used for at least 300 days in a year, payback period = USD 1,867/(USD 1.464 × 300) = 4.3 years. In this simple economic analysis, labor charge for gathering fuel wood is not considered – but this will further reduce the payback period as gathering firewood has an economic price (McPeak 2003). This means that, if farmers adopt the technology, it will take them at most 4.3 years to recoup their investments. Thereafter they will continue enjoying the benefits of the technology for at least 15 years, which is the average lifespan for flat-plate solar water heaters (Duffie and Beckman 2006), depending on the system, how well it is maintained, insolation, duration of sunshine, energy price and hot water consumption.

CONCLUSIONS AND RECOMMENDATIONS

A low-cost method to pasteurize milk with solar energy has been developed. The device can pasteurize 40 L of milk in approximately 1.3 ± 0.5 h when the solar insolation ranged from 700 to 1,000 W/m^2/day and temperature ranged from 22 to 31C. This low-cost solar milk pasteurizer is suitable for use in arid pastoral areas that do not have access to grid electricity but have plenty of solar radiation and camel milk marketing is an important income source, and where most of the milk is boiled using firewood. The use of firewood in arid areas is not sustainable because of its slow rate of renewal. In contrast to the use of fossil fuels, utilization of solar energy eliminates generation of greenhouse and acid producing gases that adversely affect the environment.

The milk pasteurizer could be improved and made even more feasible by optimizing the dimensions of the solar collector and the tank, and providing a means of continuous agitation of the milk to reduce the heating time and hence the total pasteurization time.

ACKNOWLEDGMENTS

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