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REVIEW ARTICLE

Application of solar thermal collectors for milk pasteurization to explore the potential of renewable energy in the dairy sector: Challenges and possibilities

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ABSTRACT

Dairy farming has become a key business to fulfill the daily milk needs in populated countries like India. Conversely, pathogenic and spoilage microorganisms in raw milk are killed by applying different heat treatments to increase shelf life, preserve quality, and ensure safety. Among the heat treatment processes used at the dairy plant, pasteurization consumes a significant amount of heat, which increases the energy demand in the dairy sector. Since milk pasteurization occurs between 65°C and 150°C, multiple solar thermal collector alternatives are available for various kinds of pasteurization processes. Employing solar thermal collectors for milk pasteurization allows the dairy sector to use free solar energy. Solar energy in milk heat treatments minimizes fuel and power consumption, reducing carbon emissions and promoting sustainability. However, solar milk pasteurization in dairy sector is limited by the large area requirement, high initial cost, and weather dependency. There have been attempts to use different types of solar thermal collectors to pasteurize the milk in an effort to replace conventional energy usage with solar energy. The parameters of milk heat treatment, primarily pasteurization, have been discussed concerning energy usage. The benefits and limitations of various solar collectors for milk pasteurization and other heating applications in the dairy sector have been addressed. Multiple

studies on integrating various solar thermal collectors with different pasteurization systems have been reviewed, summarized, and concluded.
Keywords: Batch pasteurization; Continuous pasteurization; LTLT pasteurization; HTST pasteurization; Milk heat treatment; Specific energy consumption; Solar milk pasteurization.

Abbreviations

ANN	Artificial Neural Network	LFC	Linear Fresnel Collector
CPC	Compound Parabolic Concentrator	PHE	Plate Heat Exchanger
ETC	Evacuated Tube Collector	PTC	Parabolic Trough Collector
FPC	Flat Plate Collector	PVT	Photovoltaic-Thermal
HHST	High Heat Short Time	PVT/IPC	Photovoltaic-Thermal Integrated Parabolic Collector
HTST	High Temperature Short Time	UHT	Ultra-High Temperature
LTLT	Low Temperature Long Time		

1. Introduction

Agriculture and dairy farming are the key businesses in Indian villages. According to statistics published in 2023, India produces over 230 million tonnes of milk annually[1]. According to Anirban Sur et al.[2], in 2020, India possessed approximately 200 million of cattle, which is a 25% share of the world's total cattle population. It enabled India's milk production sector to grow at a quicker pace of 4.7% annual growth rate in the last 15 years, compared to other significant milk-producing countries, and it has increased to 210 million tonnes in 2020-21[3,4]. The daily milk consumption in India is 427 grams per capita, which is against the world average of 322 grams per capita in 2022[3]. The practice of raw milk consumption will lead human beings to health hazards as it contains microbial pathogens like viruses, pathogenic bacteria, and other pathogens. The sources of microbial pathogens in raw milk are the milk from infected dams or contamination during handling or on-farm[5]. Hence, it is required to kill the microbial pathogens present in the milk. Pasteurization is a heat treatment that kills the microbial pathogens and spoilage microorganisms in the milk and its liquid products. Also, reduce it to a level where they do not constitute a significant health hazard with minimal chemical, physical, and organoleptic changes. It also prolongs the shelf life of milk or liquid milk products[6–8].

The pasteurization process consumes a crucial amount of energy in dairy plants, received from fossil fuel or electrical based steam generators[9]. In the present scenario of energy crises and environmental problems, there is a need for the reduction of energy costs by replacement of fossil fuel based sources with renewable sources. Thermal energy needed in the milk pasteurization process can be fulfilled by renewable energy sourced from solar energy, geothermal energy, biomass, or waste heat based on their availability and viability on-site[10–12].

India is situated in a region with ample solar energy, ranging from 4 to 7 kWh/m^2 per day, having about 300 sunshine days yearly[12]. This lavishness of solar energy, coupled with the concept of milk pasteurization, explores a new area of application in dairy industries. The idea of integrating solar energy into the milk pasteurization process in Indian dairy industries becomes a sustainable solution to address energy crises and environmental issues[13].

Various reviews on the application of solar energy for milk pasteurization focused on important aspect of solar collectors and heat exchanger for solar milk pasteurization and findings of various researchers have been done earlier[12–14]. None of them have addressed the energy demand in various milk pasteurization processes, the suitability of solar collectors for various heat treatments, or the feasibility of integrating solar collectors in various dairy sites. The objectives of the presented study are:

- To review thermal energy demand in the dairy industry for various pasteurization processes, to represent the suitability of solar collectors for various milk heat treatments.
- To review and summarize the findings on solar thermal collector-based milk pasteurization.
- To explore the capabilities and limitations of various solar thermal collectors' applications for milk pasteurization at various dairy sites.

Hence, this review aims to explore the utilization of solar thermal collectors for milk pasteurization in the dairy sector as a sustainable and eco-friendly alternative to conventional fossil fuel-based sources.

2. Milk and its heat treatment

Milk is a colloidal water suspension containing emulsified globules of fat, proteins, carbohydrates, lactose, and minerals like potassium, sodium, calcium, magnesium, phosphates, vitamins, and enzymes[6,7,14,15]. Milk contains 88% water; thus, the thermo-physical properties of milk are nearly similar to the water. Thermo-physical properties as the function of temperature, suggested by various authors in different relations[15–21]. The most suitable relations for properties of milk having less than 10% fat are given in **Table 1**[20].

Table 1. Thermo-physical properties of milk[21].

Properties	Value
Boiling point	373.17 K
Freezing point	272.45 K
Heat capacity, C_p	$3744.48 + 1.15T + 3.93\times10^{-3}T^2$; J/kg
Density, ρ	$1042.01 - 0.37T + 0.36\times10^{-3}T^2$; kg/m^3
Thermal conductivity, k	$0.49 + 2.23\times10^{-3}T - 1.08\times10^{-5}T^2$;W/m.°C
Viscosity, μ	$2.82 - 4.58\times10^{-2}T + 2.83\times10^{-4}T^2$; kg/s.m

Note: T is the temperature of milk in °C

2.1 Milk heat treatments

Pathogenic microorganisms in milk grow very fast in the temperature range of 20-40ºC[8]. Most pathogenic microorganisms destroy above the temperature of 65ºC[22] and entirely with spoilage microorganisms and peroxidase above 80ºC[23]. Non-pathogenic gram-positive bacteria grow rapidly in the temperature range of 40-60ºC and may withstand temperatures up to 75ºC, lead to milk spoilage[8]. Various heat treatments of milk are conducted at temperatures ranging from 65°C to 150ºC with its holding time for the thermal death of pathogenic and spoilage bacteria, as shown in **table 2**. However, the harsh heat treatment of milk causes milk browning in color, development of a cooked flavor, loss of nutritional quality, impairment of rennet-ability, and inactivation of bacterial inhibitors in the milk[6,8,24]. Hence, to meet pasteurization standards and ensure milk quality, temperature and holding time are crucial parameters for milk heat treatment and must be precisely maintained as per **table 3**.

Table 2. Types of milk heat treatments[21].

Heat treatment type		Typical Product	Temperature	Holding Time	Typical Storage	Shelf life
Thermalization		Milk	60 – 69°C	10-20 s	Refrigerated	3 days
Batch Type	Vat or LTLT Pasteurization	Milk	63 – 68°C	30 min	Refrigerated	7 days
Continuous Type	Flash or HTST Pasteurization	Milk	72°C	15 s	Refrigerated	21 days
		products with more than 10% fat (%w/w)	74.4°C	15 s	Refrigerated	
	HHST Pasteurization	Milk	89°C	1 s	Refrigerated	
			90°C	0.5 s		
			93.8°C	0.1 s		
			96.2°C	0.05 s		
			100°C	0.01 s		
	UHT Pasteurization	Milk	135-150°C	4-15 s	Room temperature	2-3 months
Sterilization		Canned or in-bottle products	115.6°C	20 min	Room temperature	1 year

Pasteurization is a heat treatment with the function of time and temperature with the objectives of warranting the safety of the consumer by killing microorganisms, inactivating enzymes, increasing shelf life, and preserving/establishing specific product properties[29,31]. According to the Australian New Zealand Food Standards Code[25,31], minimum holding time and temperature combinations for pasteurization of milk with less than 10% fat are given in **Table 3**[26,31].

The batch pasteurization process, also known as vat pasteurization, holder pasteurization, or LTLT pasteurization, is shown in Figure 1(a). It is the simplest and oldest process in which milk is heated batch-wise in a jacketed vat at a low temperature of 63ºC to 68ºC for a high holding time of 30 min[28]. In the batch pasteurization process, steam is used for uniform heating of milk, and it is ensured that variation in milk temperature during the holding time should not exceed 1ºC[31].

Nowadays, continuous pasteurization process, also known as flash pasteurization or HTST pasteurization, is widely used as it is continuous, fast, energy efficient, safe, and prevents milk quality loss, however it may result in a cooked taste[32]. Layout of continuous pasteurization is shown Figure 1(b). The best combinations of HTST Pasteurization are 71.5ºC for 20 s, 72ºC for 15 s, and 89ºC for 1 s[27].

Table 3. Time-temperature combinations for continuous pasteurization of milk[27,33].

Sr. No.	Minimum Holding Time (s)	Minimum temperature (ºC)	Sr. No.	Minimum Holding Time (s)	Minimum temperature (ºC)	Sr. No.	Minimum Holding Time (s)	Minimum temperature (ºC)
1	0.01	100	11	13	72.3	21	26	70.9
2	0.05	96	12	14	72.1	22	28	70.8
3	0.1	94	13	15	72	23	30	70.7
4	0.5	90	14	16	71.9	24	35	70.4
5	1	89	15	17	71.8	25	40	70.1
6	8	73.4	16	18	71.7	26	45	69.9
7	9	73.1	17	19	71.6	27	50	69.7
8	10	72.8	18	20	71.5	28	55	69.5
9	11	72.7	19	22	71.3	29	60	69.3
10	12	72.5	20	24	71.1			

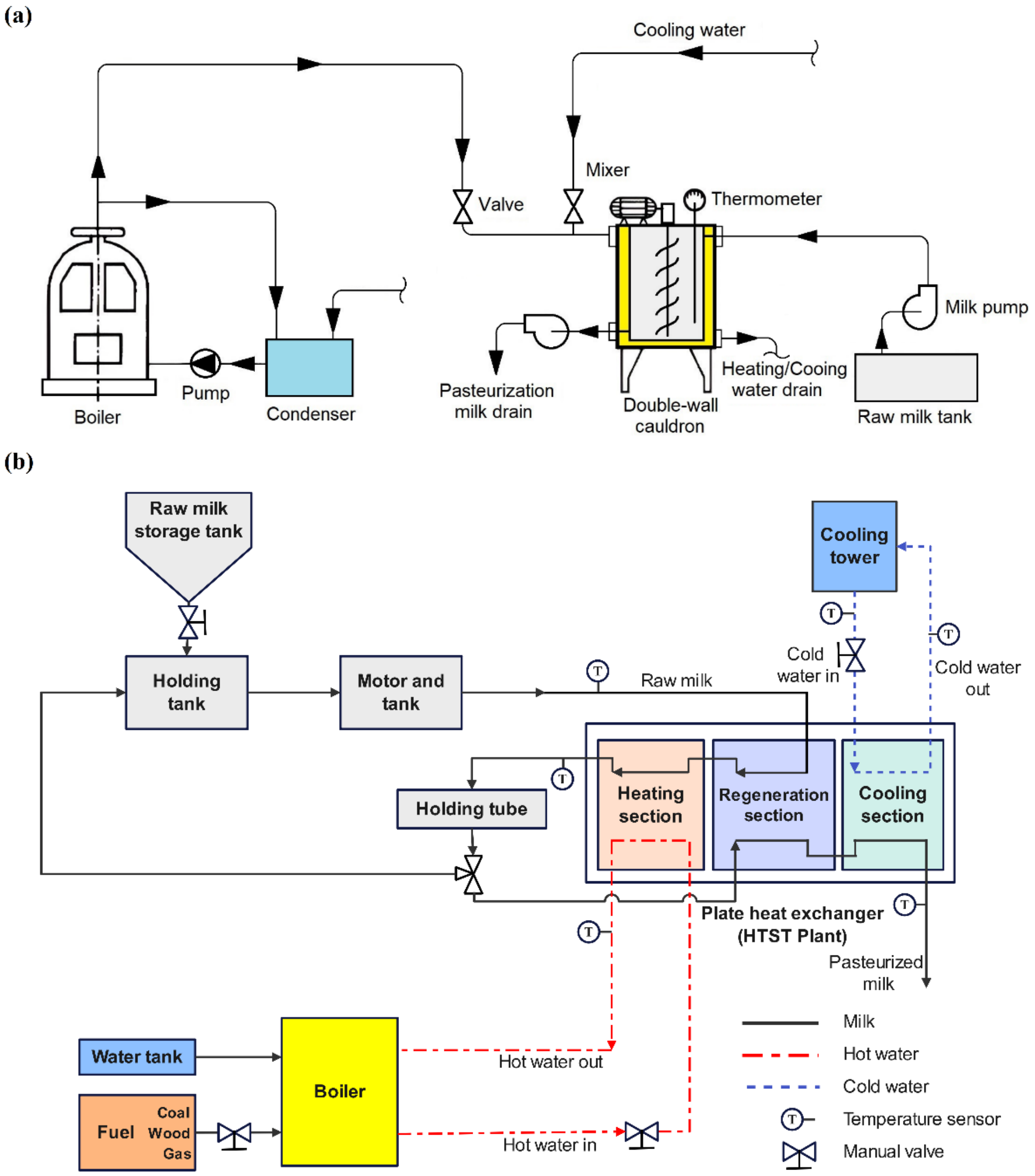

Figure 1. Conventional low-heat milk pasteurization systems (a) Batch pasteurization system[34] (b) Continuous pasteurization system[35].

2.2 Energy consumption in the pasteurization process

The pasteurization process holds a significant share of energy consumption in dairy plants. It consumes approximate 40% of thermal energy of total energy consumption in a typical dairy industry[36,37]. The demand of thermal energy for various milk heat treatments is varied from 180 to 2100 kJ/kg of milk which is fulfilled by steam or hot water from boilers or electric heaters runs on fossil fuel or electricity in conventional dairy plants[9,38–41]. **Table 4** shows energy consumption in various processes of the HTST milk pasteurization method in a typical dairy plant. **Table 5** shows thermal and electrical energy consumption in various pasteurization processes in a typical dairy plant.

Table 4. Energy consumption in various processes in HTST milk pasteurization method at a typical dairy plant[42].

Process sequence	Specific energy consumption for HTST pasteurization (kJ/kg of milk)					Percentage share (%)
	Steam (Thermal energy)	Transportation	Refrigeration and cooling	Miscellaneous Electrical energy	Total	
Reception and storage	-	30.2	41.9	-	72.1	16.29
Clarification/ Standardization	-	-	-	20.9	20.9	4.73
Separation	-	-	-	41.9	41.9	9.46
Pasteurization	**214.0**	**-**	**-**	**-**	**214.0**	**48.3**
Homogenization	-	-	-	2.3	2.3	0.53
Cooling	-	-	19.8	-	19.8	4.47
Deodorization	5.8	-	-	-	5.8	1.32
Storage before packing	-	-	20.9	-	20.9	4.73
Packing	-	3.5	-	-	3.5	0.71
End product storage	-	-	41.9	-	41.9	9.46
Total	219.8	33.7	124.4	65.1	443.1	100

Table 5. Specific energy demand for various milk heat treatment in a typical dairy plant[8,25,27,41].

Type of milk process	Temperature range (°C)	Specific energy demand (kJ/kg of milk)	
		Thermal energy	Electrical energy
Continuous pasteurization	70-96	250	180
UHT pasteurization	135-150	360	325
Sterilization	108-111	720	250
drying/milk power	180-200	2100	325
Evaporated and condensed milk	116-150	1060	220

Ozyurt et al.[43]reported that continuous type pasteurization with heat pump consumes 2.8 and 1.9 times less energy compared to batch and convectional continuous pasteurization respectively as shown in **Table 6**. However, the heat pump consumes electrical energy, which is high-grade energy.

Kazimirova et al.[44] reported that continuous type pasteurization requires 51.69 kJ/kg of heat, with 82% heat regeneration in the regenerator section. Thus, a continuous type pasteurization system is more energy efficient than a vat type as it can regenerate up to 90% heat, which is impossible in a batch pasteurization system.

Table 6. Comparison between energy consumption in conventional pasteurization without and with heat pump[43].

Type of energy for the pasteurization process	Batch type (Double jacketed vat) (kJ/kg of milk)	Continuous type (Plate heat exchanger) (kJ/kg of milk)	Continuous type with heat pump (kJ/kg of milk)
Heat energy	494.49	248.66	---
Electrical energy	5.93	98.2	182.8
Equivalent energy of cooling water	9.45	---	---
Total energy	509.87	346.86	182.8

2.3 Applications of solar collectors in dairy plants

Heat demand by various applications in dairy industries can fulfilled partly or fully by various solar thermal collectors according to application temperature and its types[40,45]. The selection of suitable solar thermal collectors for various applications in dairy plants is according to its temperature range, as shown in **Table 7**. Non-tracking type solar collectors are more suitable for thermalization, LTLT, HTST, and HHST pasteurization processes, while tracking concentrating type solar collectors are preferable for sterilization, HHST, and UHT pasteurizations, according to the range of application temperature[40,46].

Table 7. Temperature range and applications of solar collectors in dairy plants[40,47,48].

Motion	Collector type	Temperature range (°C)	Applications in dairy plant
Stationary	Flat plate collector	30-80	Thermalization, Batch pasteurization and High temperature short time pasteurization, Milk concentrates, Milk preheating, Boiler feed water, Cleaning hot water
	Evacuated tube collector	50-200	
	Compound parabolic concentrator	60-240	High temperature short time, High heat short time, and Ultra-high temperature pasteurization, Sterilisation, Drying, Steam for process heating, Absorption chiller, Adsorption chiller
Single-axis tracking		60-300	
	Linear Fresnel collector	60-250	
	Parabolic trough collector	60-300	
	Cylindrical trough collector	60-300	
Two-axes tracking	Parabolic dish reflector	100-500	High heat short time and Ultra-high temperature pasteurization, Sterilisation, Drying, Steam for process heating, Absorption chiller

3. Application of solar thermal collectors in milk Pasteurization

Milk pasteurization is an energy-intensive process that operates at temperatures ranging from 65°C to 150°C. This temperature range allows for the utilization of various kinds of solar collectors in the pasteurization of milk. Researchers attempted pasteurization of milk mainly by FPC, ETC, or concentrating type solar collectors with batch type or continuous type pasteurization systems.

3.1 Milk pasteurization using FPC

Since solar energy is intermittent and fluctuates throughout the day, precise temperature and holding time control is necessary for achieving high-quality pasteurization of milk. Nielsen et al.[49] developed a control system to achieve a constant pasteurization temperature from the FPC panel without energy storage. They developed a small-scale solar milk pasteurization system with a capacity of 1000 L/day milk, at the rate of 200 L/hr. It was equipped with an FPC of 10kW, and heat exchanger cum pasteurizer with a closed-loop control system. Water was used as the heat transfer fluid in the primary circuit to transfer heat from the solar panel to the heat exchanger or pasteurizer at 100°C, where milk was heated to its pasteurization temperature in the range of 72°C to 75°C. A developed close control system regulated milk flow rate to control milk outlet temperature, based on the relation represented by below equation, derived from the pasteurization curve. The developed control system could control the pasteurization temperature in the range of 72°C to 75°C.

$$\text{Milk flowrate}, m_m = \frac{V_h \rho_m e^{0.4353.T_{mo}}}{5.10^{14}} \quad (1)$$

Where, V_h = holing volume in holding tank in m^3, ρ_m = density of milk in kg/m^3, T_{mo} = measured milk temp at pasteurizer outlet in °C.

Wayua et al.[50] used an FPC to utilize solar energy for the pasteurization of camel milk in the arid area of Northern Kenya, where milk marketing is the major source of income for local people. The Kenya Arid and Semi-arid Lands Research program funded the entire project to develop a low-cost solar milk pasteurization system. In the developed system, hot water from FPC was used to pasteurize the milk using the batch pasteurization method at a temperature of 63°C. Experiments were carried out with various batch sizes from 20 L to 70 L at every 10 L interval during the availability of solar insolation from 700 to 1000 W/(m².day). Optimum results were achieved at 40 L batch capacity by reaching a milk pasteurization temperature of 69.7°C in 1.3±0.5 hr. Quality of pasteurization was ensured by total bacterial counts (TBC) and coliform counts of raw and pasteurized milk. Author reported in the various raw milk samples, TBC ranged from 750 x 10^3 to 20000 x 10^3 cfu/ml, whereas coliform counts ranged from 10 to 1700 cfu/ml. In pasteurized milk, TBC was decreased to less than 10 cfu/ml, and coliform levels were negative. However, according to Kanya requirements for pasteurized milk, the TBC value should be negative right after pasteurization.

A three-layer feed-forward ANN model was developed by Wayua et al.[51] to predict the outlet temperature of pasteurized milk based on variables and compared with experimental results. Maximum value of pasteurization was predicted at 64.3°C on 13:00 h standard local time. An optimum model of the ANN model was found with one hidden layer and four neurons in the hidden layer. Minimum mean square error, mean relative error, and R^2 were obtained at 5.23°C, 3.71%, and 0.89, respectively, which predicted pasteurized milk temperature with maximum and minimum deviation of 5.3°C and 0.1°C accordingly. Thus, ANN is one of the design tools to predict the outputs of solar milk pasteurization systems.

Mutasher et al.[52] developed a low-cost portable solar milk pasteurizer in Suhar City, Oman. 1.5 m^2 FPC was used to heat the water for the pasteurization of milk with the vat pasteurization method. Comparison of results with FPC tilt angle at 24°C and 27°C were done in May. The author achieved a maximum temperature of 68°C with a tilt angle of 27°C, which enabled the system to pasteurize 28 L milk per day with a holding time of 30 min.

Panchal et al.[53] pasteurized milk using heat from an FPC. A concentric tube heat exchanger was used to pasteurize the milk with hot water coming from FPC. Experiments were conducted with hot water flow rates of 2, 3, and 5 L/min and milk flow rates of 0.5, 0.7, and 1 L/min during March and April. The capacity of the developed system was identified at pasteurization temperatures of 63°C and 73°C by LTLT and HTST methods, respectively. A control system was developed to divert the milk flow toward the holding tube for 30 min holding when the milk temperature reaches 63°C and divert directly toward the cooling system when the temperature reaches 73°C. It was concluded that minimum log mean temperature difference, maximum heat transfer rate, and effectiveness were achieved at the higher flow rate of hot water and lower flow rate of milk.

Single cover FPC without and with reflectors, along with the LTLT batch pasteurization method, was used to pasteurize the milk by Tigabe et al.[54], as shown in **Figure 2**. Performance of FPC without and with reflectors was compared to optimize the milk pasteurization quantity, outlet temperature, and thermal efficiency. The maximum pasteurization temperature achieved was 49.4°C without a reflector and 52.2°C with a reflector with capacities of 60.2 and 70.2 L/day, respectively, in November at Ethiopia (12.6°N, 34.446°E). However, batch pasteurization required 63˚C to 68˚C for a holding time of 30 min. The milk flow rate of 0.01 kg/s was fixed for comparison. Maximum efficiency of 51.8% was obtained in FPC with a reflector in November. The quality of pasteurized milk was evaluated using the methylene blue reduction test. The author claimed that the decolorization time for raw milk was 1.10 hours, indicating low milk quality; however, after pasteurization of milk using a solar milk pasteurization system, the decolorization time was increased to 6.25 hours, indicating good milk quality.

Figure 2. Experimental setup of milk pasteurization using FPC[54].

The maximum temperature of pasteurized milk achieved by FPC in various experimental work ranged from 52.2°C to 73°C with the milk capacity of up to 70 L/day. Hence it is limited for LTLT pasteurization with small capacity due to its lower output temperature. FPC offers thermal efficiency ranging from 50% to 76% in the warm climatic condition[55–57]. Its design simplicity and improved thermal efficiency make it popular in torrid zones. Absence of moving parts in FPC gives advantages of low maintenance cost, low operating cost, and high reliability with a long-life span of 25 years[58]. Its limitations are lower output temperature and significant heat losses in cold climates than other solar collectors. Hence it has limited application in cold climatic regions. Due to its lower specific thermal output, large collector surface is required to fulfill the thermal energy demand of dairy industry, which leads to higher initial cost and large installation space.

3.2 Milk pasteurization using ETC

Quijera et al.[59] proposed the integration of a solar thermal system in a dairy plant situated in Spain near the Basque Country, as shown in **Figure 3**. Pinch and exergy tools were applied to propose the thermo-solar system integration with existing dairy plants to reduce energy consumption from gas boiler. The plant required 3780 kWh energy per day, which came from a gas-fired boiler. From 8 am to 1 pm, 20497 kg/batch of milk was pasteurized by the HTST method at 75°C, which needed 904 kWh/batch energy at a rate of 181 kW. As an optimum solution, ETC with a heat pipe having 2738 m^2 field area and 1939.2 m^2 absorber area was proposed to supply hot water at 95°C for the pasteurization process. This system would supply 100% energy fraction from solar energy to the plant from April to October and rest of the period shortfall energy would supply by boiler as shown in **Figure 4**. More than 70% of natural gas consumption might be reduced by the proposed integration of solar systems[9].

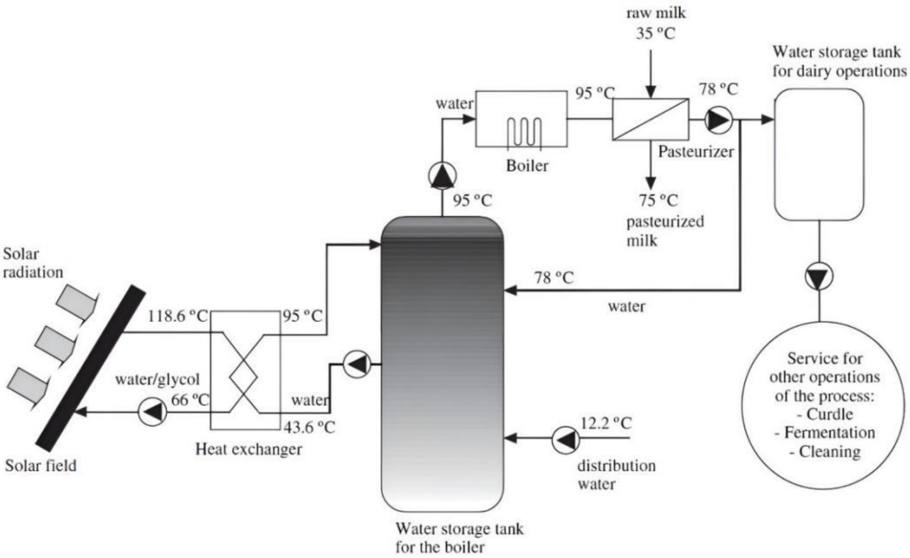

Figure 3. Proposed layout of thermo-solar system integration in dairy plant[9].

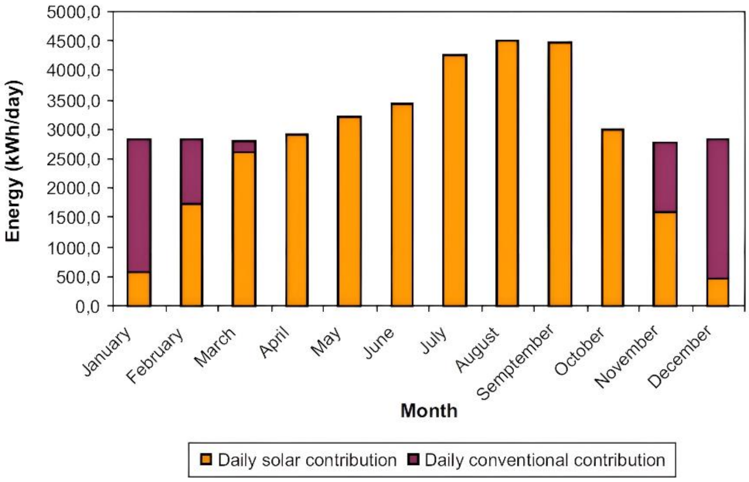

Figure 4. Daily average annual contribution of solar and conventional energy source[9].

Lazaar et al.[60] designed and developed a solar pasteurization system by integrating ETC with a PHE and absorption chiller for small production units to minimize the rejection of milk during transportation. The schematic diagram of the developed system is shown in **Figure 5**. Two heat pumps were used to simulate the inlet conditions of hot and cold fluids of PHE. The maximum effectiveness of PHE achieved was 80% at a hot water flow of 386 L/hr and 80ºC. The author has reported that two tubes of ETC provide 10520 kJ of required heat for the pasteurization of milk from 25ºC to 73ºC.

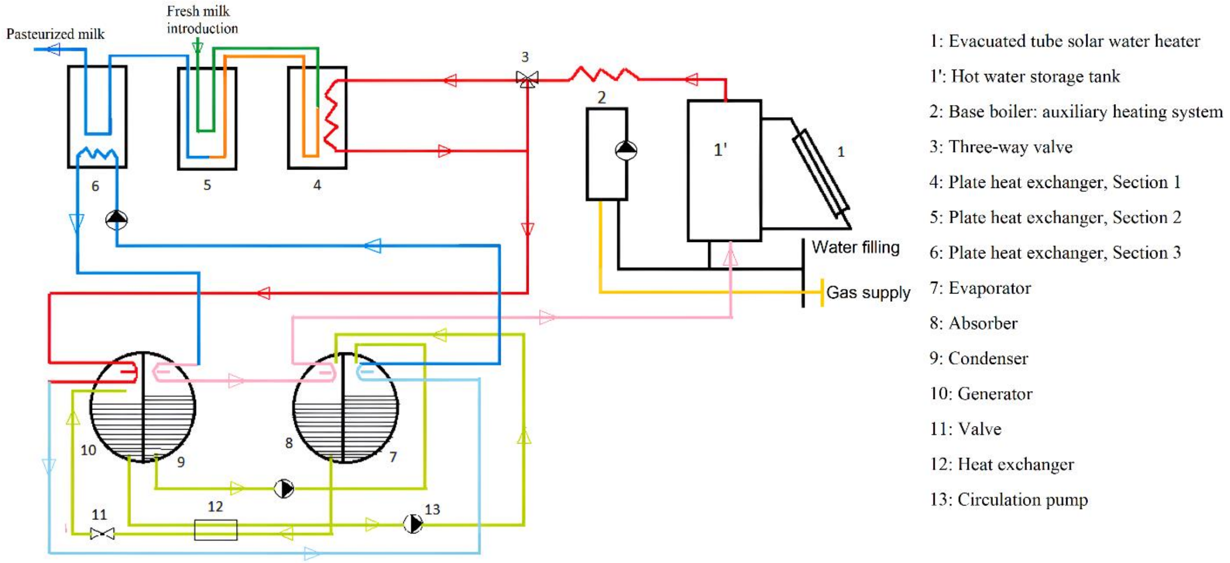

Figure 5. Schematic diagram of solar milk pasteurization system with ETC, PHE, and absorption chiller[60].

Ramkumar et al.[61] used cylindrical parabolic concentrators with ETC for the pasteurization of milk at 73°C with various flow rates of 5, 10, and 15 L/min from 11 am to 2 pm with the HTST method. After pasteurization milk was delivered to charcoal and methanol based solar adsorption chiller and cooled at 5°C to 6°C to store in a 200 L tank. A pasteurization temperature of 73°C was achieved at 5 L/min flow rate at 2 pm. For the pasteurization of 200 L of milk at a temperature of 70°C and 78°C, measured heat requirements were 5.8 kWh and 5.5 kWh respectively, with 95.25% efficiency. It was concluded that ETC is a more efficient, compact, durable, easy-to-install, low-maintenance, and cost-effective solution for milk pasteurization.

Reported work shows that ETCs provide higher temperature than FPCs, making them more suitable for milk pasteurization. They are used to pasteurize the milk at 73–75°C using HTST method. ETCs are more efficient than FPCs, particularly in cold climatic conditions[62]. The vacuum enclosing the absorber prevents convective heat loss, making it more suitable for cold climates. It gives efficiency ranging from 45% to 76%[63,64]. Compared to other collectors ETC can perform well during cloudy condition due to its ability to capture beam and diffuse solar radiation effectively. Hence ETC has batter performance compared to other collectors in variable climatic conditions. Like FPC, ETC also has advantage of low maintenance, low operating cost, high reliability with long life-span up to 30 years[63]. Initial cost of ETC collector is comparatively lower than FPC gives lowest payback period of 2.8 years[65].

3.3 Milk pasteurization using solar concentrators

In 1978 there was an early attempt to develop a solar milk pasteurization system by Pandey and Gupta[66]. They used a cylindrical parabolic reflector and a secondary reflector with a black-painted co-axial stainless steel pipe absorber placed at the focal point. Milk flowed through the annular space of this co-axial pipe and was controlled by a valve to maintain 78°C. The developed system could pasteurise 100 L of milk per day by the HTST pasteurization method.

Franco et al.[67]designed and developed a low-cost on-farm pasteurizer using a manual tracking type Fresnel solar concentrator (reflector) in Salta, Argentina, as shown in **Figure 6**. The vat pasteurization process was selected and operated at 62-65ºC. Fresnel solar concentrator was used to receive solar energy and concentrate it on a steam generator, where 1000 W heating power was developed and steam generated at the rate of 1 kg/min at 100°C with 50% efficiency. The pasteurization vat of 10 L milk capacity received steam from the steam generator and pasteurized 30 L milk in 3 batches of 10 L/day.

The startup time of the developed pasteurizer was noted as 75 min which was the time to generate steam in a steam generator. Manually operated solar tracking and the small size and capacity of the device make it portable, low-cost and suitable for on-farm use.

Figure 6. On-farm milk pasteurization system using Fresnel solar concentrator[67].

Alkasim and Andrew[68] constructed a milk pasteurization system using a parabolic disc concentrator. A parabolic disc of 1.8 m in diameter was used to concentrate solar radiation at a steam generator placed at the focal point. Generated steam was supplied to the pasteurization unit which has a 6 L capacity of milk. All three methods, LTLT, HTST, and HHST, were performed at 63°C with 30 min, 72°C with 15 s, and 89°C with 1 s holing, respectively. 64°C in 60 min, 73°C in 70 min, and 89°C in 85 min for LTLT, HTST, and HHST pasteurization, respectively, were achieved under the clear sky condition between 11:00 and 15:00 Hrs. During the experiment 28% optical efficiency of the parabolic dish, 56% pasteurization unit efficiency, and 7.12 W/K-m^2 heat loss factor were obtained. Sur et al.[2] constricted a parabolic concentrator with an evacuated glass tube to pasteurize the milk for small cattle farms at a remote place as shown in **Figure 7**. The parabolic concentrator was designed in such a way that it maintains constant milk outlet temperature for quality pasteurization by the continuous HTST pasteurization method with a 150 L/day capacity. To enhance solar infra-ray absorption capacity and minimize heat losses, an evacuated glass tube was placed at the focal point of the concentrator as an absorber. Experiments were performed for various flow rates between 9hrs and 15hrs during January. Maximum pasteurization temperature was 75°C, achieved at 5 L/min flow rate in the stipulated time duration from 11 am to 1 pm and held for 30 min to achieve pasteurization temperature of milk at 75°C with a milk flow rate of 5 L/min in the stipulated time duration from 11 am to 1 pm After pasteurization, milk was chilled up to 5°C by the adsorption chiller run by solar energy supplied by FPC.

Figure 7. Milk pasteurization by parabolic concentrator with evacuated glass tube[2].

Setiawan et al.[69] used a 4 m^2 evacuated panel with reflective arrays to heat the water for the batch pasteurization process of milk in Indonesia. The large volume of flat plate accumulator was placed at the bottom of absorber pipes inside the collector unit to collect the hot water coming from absorber pipes and to dampen the variation of water temperature inside it. The position of reflective arrays fitted at the bottom of the absorber pipes of the collector was controlled by a 12 W DC motor to control the solar radiation reflected on the absorber pipe inside the solar collector to maintain the water temperature at 82°C inside the accumulator. The pump circulated water at this temperature from the accumulator through a jacketed pasteurization vat. It was reported that 6.75 L of milk took 12 min to be pasteurized at 70°C temperature when hot water was supplied at 85°C during peak solar irradiance, providing 1.9 kWh energy with 47% efficiency of solar collector. A maximum of 5 batches of 6.75 L were pasteurized in a day, making it suitable for small-scale pasteurization systems for farms and remote locations.

Zahira et al.[70] made a low-cost solar cooker-like milk pasteurizer using shipping cardboard, glass, aluminum foil, and a metal tray. Silver-coated cardboard was used as a reflector to concentrate solar radiation on the back painted metal tray containing milk. Pasteurization of milk was done by batch pasteurization method at temperature ranges from 63°C to 78°C. It took 200 min to achieve the pasteurization temperature of 78°C during 10 to 14 hrs. in the summer season. After pasteurization, milk was tested using an alkaline phosphate test, which gave a light brown color, indicating that pasteurization had been perfectly.

3.3.1 Comparison between solar concentrator and ETC for milk pasteurization

A comparative study between solar concentrator and ETC, for integration with milk pasteurization system of 200 L batch capacity was carried out by Khan et al.[71]. Scheffler fixed focus solar concentrator with receiver was used to generate steam for milk pasteurization. In comparison, ETC with heat pipe was used to achieve glycol-water at 100°C for pasteurization. A schematic diagram of solar milk pasteurization systems coupled with Scheffler fix focus solar concentrator and ETC is shown in **Figure 8**. According to Khan et al.[71], 3.566 kWh thermal energy at 2.67 kW was required to perform batch pasteurization of 100 L milk from 30°C to 63°C with 30 min holding time.

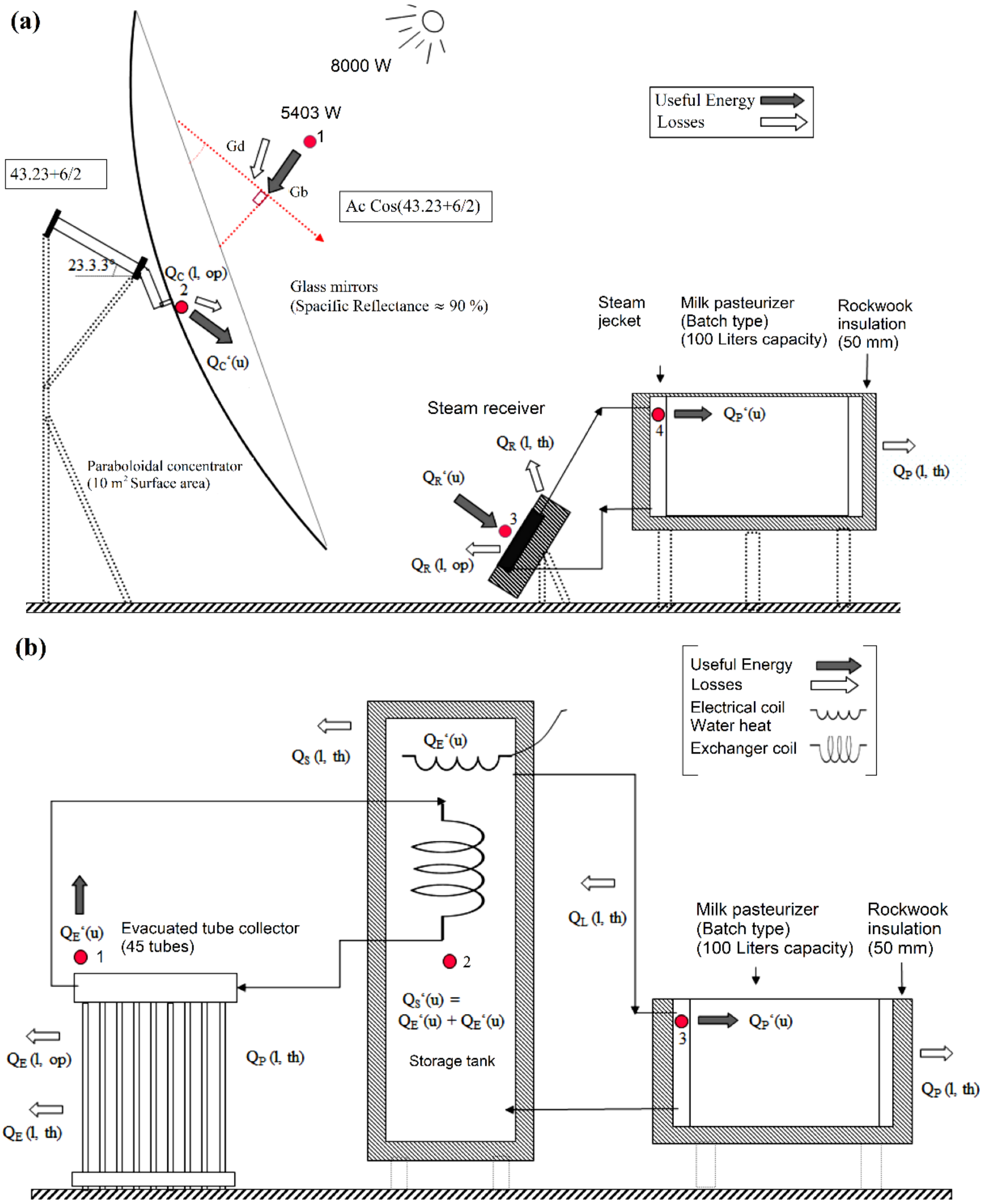

Figure 8. Schematic diagram of solar milk pasteurization system (a) Integrated with solar concentrator (b) Integrated with evacuated tube collector[71].

To fulfill the mentioned requirement, solar concentrator supplied 3.566 kWh energy, against 6.6 kWh total available solar energy on 6.75 m^2 aperture area, with 54% efficiency, while ETC supplied 3.91 kWh, against 5.49 kWh total available solar energy on 4.695 m^2 aperture area, with 71% efficiency. It was concluded that ETC was more efficient and simpler than solar concentrators, while ETC produced lower thermal power than solar concentrators.

Researchers experimented with different types of concentrated solar collectors to generate steam for milk pasteurization with both LTLT and HTST techniques on a small scale. The efficiency reported in the experiments ranged from 47% to 56%. PTC, Fresnel concentrator, parabolic disc concentrator and Scheffler disc are used in various milk pasteurization processes. Among them, PTCs are widely used for milk pasteurization in countries situated in temperate zones[72], where solar intensity is inadequate for FPCs and ETCs. Solar tracking and beam radiation concentration are the key features of concentrating collectors that allow for increased solar energy collection and consistent output throughout the day, where FPCs and ETCs are lacking. Concentrating collators are preferable only for medium temperature (200°C to 300°C) to high temperature (300°C to 350°C) applications, while for low temperature ETCs are preferable[73]. Concentrating collectors capture only beam radiations, while FPC and ETC capture both, beam and diffuse[74]. Hence, concentrating collectors are efficient only in clear sky conditions, with higher beam radiation fraction. In comparison with FPC and ETC, concentrating solar collectors have limitations such as reduced efficiency in cloudy or hazy conditions[73], higher optical loss[75], more complexity, requiring a large field area[74], higher initial costs, higher maintenance, and operating costs due to tracking systems and frequent reflector cleaning, shorter lifespan, and a longer payback period ranging from 17 to 24 years[76].

3.4 Milk pasteurization using PVT panel

PVT hybrid solar collector is a fusion of FPC and solar photovoltaic collector. It allows the simultaneous production of heat and electricity using a single panel[77,78].

Akmese et al.[79]integrated a monocrystalline PVT panel and heat pump with a milk pasteurization plant with 100 L capacity and a maximum flow rate of 150 L/hr, as shown in **Figure 9**. Thermal energy received from the PVT panel was utilized to pre-heat the boiler water used for pasteurization purposes, while electrical energy received from the PVT panel was used to run the heat pump.

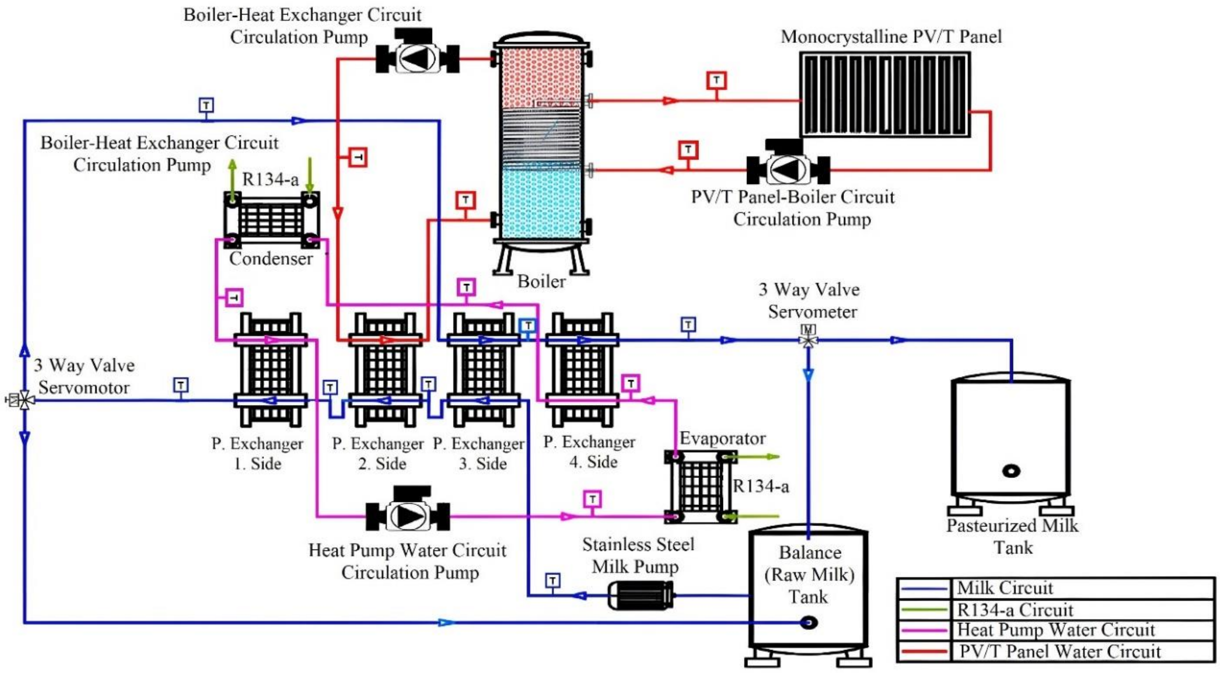

Figure 9. Schematic diagram of PVT system assisted heat pump based pasteurization system[79].

The effect of various operating parameters like solar insolation, water flow rate, and outlet temperature of water on the thermal and electrical efficiency of PVT panels were investigated and compared with conventional systems. The author reported that, a PVT assisted heat pump systems saves 73.3%, 60.7% and 25.5% energy compered to convectional vat pasteurization, continuous pasteurization and heat pump integrated contentious pasteurization systems respectively for the same capacity. Cooling of the PV surface by feed water increased PV panel efficiency. At lower solar irradiance of 800 W/m^2 higher PV panel efficiency was noticed while at higher solar irradiance at 1200 W/m^2 higher thermal efficiency of PVT system was noticed.

The integration of a CPC with a PVT panel increases heat and electrical production per unit area of the panel, hence reducing the area required for the panel to meet the demands for heating and electricity. Meraj et al.[80] proposed the integration of PVT system and CPC to develop a PVT/IPC collector as shown in **Figure 10**. Variation in the number of PVT/IPC, length of collector, packing factor of CPC, mass flow rate of thermal fluid, and mass flow rate of milk was simulated to find optimum results for the location of New Delhi, India.

The author reported that achieving pasteurization temperature at 72℃ of milk from 10 am to 4 pm requires 2.1m long ten PVT/IPC panels connected in series with a CPC packing factor of 0.25, mass flow rate of heating fluid (water) at 0.05 kg/s and mass flow rate of milk at 0.01 kg/s. The author proposed that with this configuration self-sustainable solar milk pasteurization system pasteurizes 216 kg of milk with the production of 5.7 kW electrical energy during a day.

Thermo-electric PVT panels can provide both heat and power for pasteurizing milk. Water-based PVT panels usually have thermal efficiencies ranging from 20% to 60% and electrical efficiencies ranging from 9% to 17%[77,81,82]. Moss et al.[83] compared the performance of PVT panel with FPC, ETC and PTC and found that PVT panels had lowest thermal efficiency compared to other collectors. Aoul et al.[84] reported that concentrated photovoltaic thermal collectors produced less energy than FPC but had a 28% lower production cost. Despite having lower thermal efficiency than dedicated solar thermal collectors, PVT panels have the advantage of producing additional electricity with reasonable efficiency. Thus, PVT panels can be integrated with milk pasteurization systems to help small milk collecting centers at electricity-deprived locations to fulfill the demand of heat and electricity.

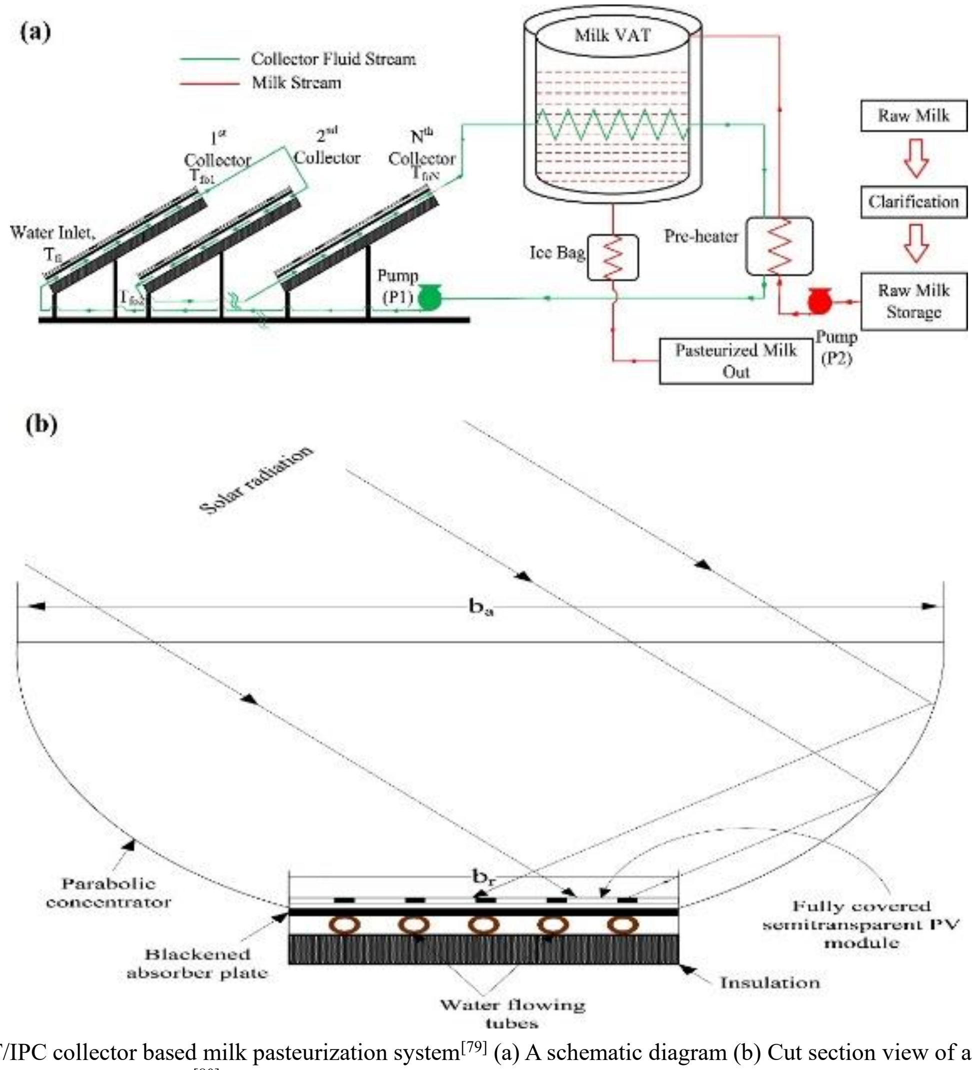

Figure 10. PVT/IPC collector based milk pasteurization system[79] (a) A schematic diagram (b) Cut section view of a fully covered semi-transparent PVT/IPC collector[80].

Researchers integrated or suggested various solar collectors with various milk pasteurization systems in diverse ways. **Table 8** summarizes the work done by several researchers on the use of solar thermal collectors for pasteurizing milk. ETCs and FPCs were commonly chosen for pasteurization using both HTST and LTLT methods. Few works have been reported using concentrating collectors and PVT panels. Most of the research is conducted in tropical countries due to the abundance of solar energy. Pasteurization temperature achieved at various locations ranges from 62°C to 89°C.

Table 8. Application of solar thermal collectors for milk pasteurization: summary.

Author and year	Title	Location	Solar thermal collector used	Pasteurization method	Temperature achieved	Capacity	Limitations
Pandey & Gupta (1978)[66]	Pasteurization of milk by solar energy	India	CPC	HTST	78°C	100 L/day	Flow rate is limited to low value at 0.416 L/min. Manual solar tracking.
Nielsen and Pedersen (2001)[49]	Solar panel based milk pasteurization	Tanzania	FPC	HTST	72 - 75°C	200 L/hr	Fluctuation in pasteurization temperature due to variation in inlet temperature coming from solar system
Franco et al. (2008)[67]	Pasteurization of goat milk using a low-cost solar concentrator	Salta, Argentina	Fresnel solar reflectors	LTLT	62-65°C	10 L/batch	Manual solar tracking. Limited efficiency of solar collector Small capacity of batch
Zahira et al. (2009)[70]	Fabrication and performance study of a solar milk pasteurizer	Pakistan	Solar cooker with mirror	LTLT	63-78°C	-	Milk pasteurization temperature achieved after 2 hrs. from starting.
Quijera et al. (2011)[9]	Integration of a solar thermal system in a dairy process	Spain	ETC	HTST	75°C	20497 L/day	Higher initial cost and large installation area need for 1.0 solar fraction of thermo-solar integration for milk pasteurization.
Wayua et al. (2013)[50]	Design and performance assessment of a flat-plate solar milk pasteurizer for arid pastoral areas of Kenya	Northen Kenya	FPC	LTLT	69.7°C	40 L/batch	Takes 1.5 hr. to achieve pasteurization temperature. Total bacterial count found slightly higher than Kenya standards for pasteurized milk.
Quijera and Labidi (2013)[59]	Pinch and exergy based thermo-solar integration in a dairy process	Spain	ETC	HTST	75°C	20497 L/day	Higher initial cost and large installation area required for solar collector installation. Payback period is 8.3 year for solar fraction 1.0
Mutasher et al. (2019)[52]	Design and development of Solar milk pasteurizer	Suhar city, Oman	FPC	LTLT	68°C	28 L/day	High startup time and pasteurization temperature achieved at 12:30 hrs.
Panchal et al. (2019)[53]	Investigation and performance analysis of solar milk pasteurisation system	Gujarat, India	FPC	LTLT and HTST	LTLT at 63°C HTST at 73°C	0.5 to 1 L/min	Higher LMTD and poor effectiveness of the pasteurizer.
Alkasim & Andrew (2020)[68]	Design, construction and implementation of a solar parabolic dish milk pasteurizer in Yola, Nigeria	Yola, Nigeria	parabolic disc collector	LTLT, HTST and HHST	LTLT at 63°C HTST at 72°C HHST at 89°C	6 L/batch	Poor system efficiency. High optical loss of parabolic dish collector.

Table 8. *(Continued)*

Author and year	Title	Location	Solar thermal collector used	Pasteurization method	Temperature achieved	Capacity	Limitations
Sur et al. (2020)[2]	Milk storage system for remote areas using solar thermal energy and adsorption cooling	Maharashtra, India	CPC with ETC	HTST	75°C	5 L/min	Pasteurization temperature achieved during 11:00 hrs. to 14:00 hrs.
Setiawan et al. (2020)[69]	Reflective array solar water heater for milk pasteurization	Indonesia	Evacuated panel with relative arrays	LTLT	70°C	6.75 L/batch	Poor thermal efficiency. Time to achieve accumulator temperature is high. It achieved required temperature at 13:00 hrs.
Lazaar et al. (2021)[60]	Parametric study of plate heat exchanger for eventual use in a solar pasteurization process designed for small milk collection centres in Tunisia	Tunisia	ETC	HTST	73°C	350 L/hr	High-pressure drop in plate heat exchanger.
Meraj et al. (2021)[80]	Effect of N-Photovoltaic thermal integrated parabolic concentrator on milk temperature for pasteurization: A simulation study	New Delhi, India	PVT integrated parabolic collector	HTST	72°C	216 kg/day	Poor thermal efficiency than dedicated solar collector. Costlier than FPC. Milk temperature is affected by cloudy and overcast weather condition. Pasteurisation temperature was achieved during.
Akmese et al. (2021)[79]	Photovoltaic thermal (PV/T) system-assisted heat pump utilization for milk pasteurization	Erzurum, Turkey	PVT panel	HTST	72°C	120-150 L/hr	Poor thermal efficiency of 51.9% at higher irradiance of 1200 W/m2.
Khan et al. (2022)[71]	Comparative thermal analyses of solar milk pasteurizers integrated with solar concentrator and evacuated tube collector	Pakistan	Scheffler fix focus solar concentrator and ETC	LTLT	63°C	100 L/batch	Maximum pasteurization temperature limited to 63°C. Poor thermal efficiency of solar consecrator. Very high startup time. Pasteurization temperature attained after 14:20 hrs.
Ramkumar et al. (2022)[61]	Implementation of Solar heat energy and adsorption cooling mechanism for milk pasteurization application	Maharashtra, India	ETC	HTST	73°C	5 L/min	Very high startup time. Milk pasteurization temperature attaindered after 14:30 hrs.
Tigabe et al. (2022)[54]	Performance analysis of the milk pasteurization process using a flat plate solar collector	Ethiopia	FPC	LTLT	52.2°C	58.59 and 69.19 L/day with and without reflector respectively	Pasteurization temperature 52.2°C is not enough as per food safety standard. Pasteurization temperature is achieved at 13:00 hrs. Effective during September and November.

Hence researchers applied varieties of solar thermal collectors with different milk pasteurization methods and achieved desired pasteurization temperature. However, many of them reported a significant delay in reaching the desired temperature initially.

Utilizing solar energy for milk heat treatments yields a significant reduction in fuel and power usage, that reducing carbon emissions and promoting sustainable practices. It encourages the on-farm pasteurization in remote regions to ensuring safe milk consumption practices. Along with its benefits, solar milk pasteurization has limitations such as weather dependency, a high initial cost, need of large area, and the necessity for an additional energy source and storage system. Weather uncertainty, diurnal and seasonal (annual) variations in solar irradiation cause fluctuations in solar collector output temperature and useful heat supply, affecting milk pasteurization efficacy. Locational variability of solar intensity and climatic conditions also impacts the specific thermal output of solar collectors. To achieve sustainable implementations of solar milk pasteurization, it needs to integrate solar collector systems with thermal storage systems and conventional energy sources.

The integration of solar collectors with heat storage devices enables a consistent heat supply, even when there are fluctuations in the output of the solar collectors caused by variable weather conditions throughout the day. The diurnal and seasonal fluctuations in solar energy can be addressed by integrating traditional heat sources, like boilers or electric heaters, with solar collectors. It supplies shortfall of heat demand when there is inadequate solar energy available. Solar fraction of integrated system is mainly influenced by onsite availability of solar irradiance, climatic condition of the site, size of installed solar field and type of solar collector. Moreover, the influence of locational variability in solar energy and climatic conditions can be mitigated by selecting appropriate solar collector based on locational feasibility.

4. Conclusions

Milk is an essential food for all humankind and must be pasteurized before consumption. To fulfill the daily need for milk in populated countries like India, 57 PJ (at a rate of 250 kJ/kg of milk) of thermal energy is required annually to produce 230 million tonnes of milk by the Indian dairy sector. Dairies rely on conventional resources to meet their energy demand, which need to be replaced with renewable and clean energy resources to address energy crises and environmental concerns. Solar energy is abundant in India due to its tropical climate and can be harnessed by solar collectors. Hence, solar collectors have significant potential in Indian dairy sector.

Since milk pasteurization occurs at temperatures between 65°C and 150°C, multiple solar thermal collector alternatives can be used for various kinds of pasteurization processes. ETC and FPC were widely utilized in LTLT and HTST pasteurization up to 85°C, whereas concentrating solar collectors were commonly used in HHST, UHT, pasteurization, and sterilization above 89°C. FPCs and ETCs were commonly used for low temperature applications, while tracking type concentrating collectors such as PTC, Scheffler disc, and LFC were used to generate high temperature pressurized steam for pasteurization and other high temperature applications such as drying and sterilizing. Furthermore, FPCs and ETCs were prevalent in dairies in tropical nations, whereas concentrating collectors were dominating in dairies in cold and temperate climates.

Implementing PVT panels is a novel way to meet the thermal and electrical requirements for milk pasteurization. To achieve pasteurization temperature with PVT panels, they need to be integrated with a heat pump or concentrator. Despite having lower thermal efficiency than ETC and FPC, PVT offers the unique benefit of producing electricity, facilitating small milk collection centers in electricity-deprived locations.

Solar-based pasteurization provides a portable and low-cost solution for on-farm milk pasteurization using solar energy, without any electricity, boilers, or geysers, in isolated dwellings and remote and arid pastoral areas. It prevents the loss of milk during handling at the milk collection center. It also encourages the peoples in remote regions for safe milk consumption practices to ensuring health and safety. Moreover, it enables the decentralized milk pasteurization at small collection centers which reduces the transportation of milk between production or collection unit and centralized processing unit.

It is required to overcome the existing challenges for sustainable development in the area of solar milk pasteurization systems by hybridization of solar collector systems with heat storage systems and existing boilers and heaters. Heat storage devices, mainly a water storage tank integrated with solar collectors, were used to supply constant heat against fluctuating solar irradiance during the day and the absence of solar irradiance at night. On the other side, variations in solar intensity during the year were overcome by the integration of conventional heat sources with solar collectors.

5. Future scope

In the era of energy crises and elevated environmental issues, it is necessary for society to substitute fossil fuel-dependent energy sources with clean and sustainable renewable energy in energy-intensive industries such as the dairy sector. Solar thermal collectors have promising potential in the dairy industry since they can partially or totally meet the energy requirement, which reduces reliance on conventional energy resources. In the diary sector, Solar milk pasteurization has promising prospects by advancement in solar technology, increased awareness of economic and environment benefits, supportive government policies and incentives, improving public health and food safety, and sustainable development in dairy sector.

Conflict of interest

The authors declare that they have no conflict of interest.

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