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Box-Type Solar Cookers: An Overview of Technological Advancement, Energy, Environmental, and Economic Benefits

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Abstract: Being one of the major energy consumers, cooking is a necessary part of daily life. Non renewable cooking fuel sources, such as wood or cow dung cause hazardous pollution and a poor ecosystem worldwide. Over the past few decades, solar-powered cooking has undergone numerous improvements. Solar cooking has been predominantly used as a substitute for reducing oil and gas dependence, increasing environmental sustainability, and reducing global warming threats. This paper talks about the recent development of the box-type solar cooker. The paper discusses the principles and classifications of various parameters that affect the performance, energy, and exergy related to the solar cooking system. In line with the sustainable development goals of the UN agenda 2030 and especially the heed to the accomplishment of SDG 7 and SDG 13, various economic factors, such as the payback period (PP), net present value (NPV), benefit–cost (B–C) ratios, internal rate of return (IRR), levelized cost of heat (LCOH), and levelized cost of cooking a meal (LCCM) have been discussed. The environmental analysis has also been presented to show the overall benefit of solar cooking. The review also focuses on the current development of a box-type solar cooker, its components, and its heat transfer characteristic. Various geometrical modifications, the use of reflectors, and transparent insulating materials that improve cooking have been discussed. The concept of energy storage in the form of Phase change material (Latent heat storage) with the latest studied designs improvements of solar cookers has been obtained to be efficient, which also help in late-evening cooking. It can be said that with better policy implications, the social and economic acceptability of the solar cooker can be achieved.

Keywords: solar cooker; box-type solar cooker; PCM; energy analysis; environmental analysis; economic analysis

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1. Introduction

Energy requirements for cooking in developing countries cover approximately 36% of the total energy requirement [1], which is significant in terms of providing a clean and green renewable energy-based comprehensive solution. The energy crisis and dependence on non-renewable resources, such as wood, oil, and gas, for cooking are the major reason for pollution, global warming, and severe health hazards to humans.

The most dominantly available renewable energy source on earth is sunshine, and quantum progress has been made to tap into this green energy option. The government of India took over a journey under the National Solar Mission (NSM) on 11 January 2010 toward active involvement from the states to envisage sustainable ecological growth and encompass the energy security needs of the country [2,3]. The amount of energy incident over India's land is approximately 5000 trillion kWh in a year, and in general, most parts receive 4–7 kWh per sq. m per day [4].

Under the umbrella of Sustainable Development Goals (SDGs) set by the United Nations in 2015, SDG 7 and SDG 13 account for affordable and clean energy and climate action, respectively [5]. Now provision of cost-effective and economical solar energy appliances, such as solar cookers (SC), in rural areas may harness both these goals. Solar energy can be used for maintaining adequate energy loads outside and inside of a building by designing energy-efficient buildings envelop [6]. Further, SDG 2 discusses the food security [7] with the aim of zero hunger, which can be realized by harnessing solar energy [6] usage in solar pumps, dryers, solar winnowers, etc., thereby enabling farmers with higher income and productivity.

Solar energy can be utilized efficiently in daylight when the quantum of sunrays is available, but there is a limitation in its usage during late-evening cooking. Challenges to the usage of solar energy include the fickle nature of sunshine, convenience, seasonal sunshine variations, diurnal availability of solar radiations, user exposure to severe solar radiations, and adjustment to the fast urban lifestyle [8–12].

The solar cooker is a fantastic eco-friendly appliance that exploits solar energy and focuses sun rays on an insulated pot wall for transmitting heat for cooking food, pasteurization, sterilization, and different end uses. Box-type solar cookers have numerous advantages associated with highly nutritious food, one-time subsidized cost, almost no maintenance and running cost, long-term usability, etc. [13]. Hence all of the above has been focused on as part of the research in this paper. Nevertheless, solar cooker without any thermal heat storage system generally faces limitations in cooking during off-sunshine periods. Therefore, the excess energy generated during low demand can be kept in a thermal energy storage system (TES), and the same may be retrieved during high-demand periods. Thermal energy can be utilized by increasing the temperature of the solid or liquid storage as specific heat or in the form of latent heat by melting or freezing the solid or liquid storage. Further energy systems can also use chemical storage methods [14,15].

As part of the study research work, comprehensive data has been collected from previous studies taken up to date with box-type solar cookers for evening cooking. Studies where simple and affordable solar cooking was carried out without the use of phase-change materials (PCM) have been discussed first. The modifications in geometry or additional reflectors and design improvements have only been accounted for in the first part of this paper. Further solar cooking with PCM enabling evening cooking has been discussed, which also shows the evolution of design development along with PCM in various studies. Solar cookers can be used outside in the direct open sun as well as inside with the help of indirect ways of cooking. Solar cookers with concentrators can be integrated within buildings [16] in such a way that cooking can be done inside the room with a SC installed as a window attachment.

This study has identified the overall design and development done in the evening SCs by different standalone approaches. As part of the study, it is configured that these standalone design improvements can be consolidated along with parametric and performance measurement calculations, thereby synergizing toward designing any cost-effective model of SC with the provision of evening cooking. This paper is unique because of its inclusive review of energy, exergy, economic and environmental analysis of box type, and recommendation of the suitable phase change material that can be used in storage-based solar cookers to enable evening cooking.

2. Types of Solar Cookers

Figure 1 shows the typical classification of SCs. Solar cookers are divided into two categories, i.e., direct and indirect cooking. Direct cooking SCs have sunrays focused straight onto the receiving area where the cooking pot is kept; however, a transient fluid transports heat from the collector to the cooking unit for indirect solar cookers.

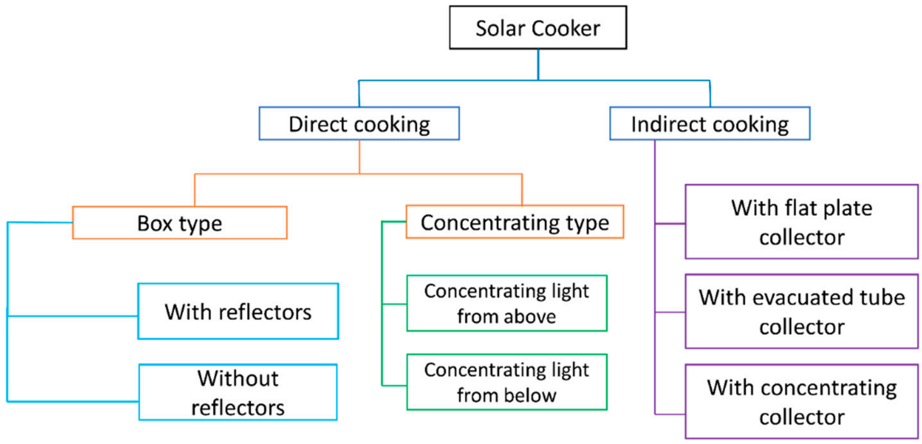

Figure 1. Classification of solar cooker. The temperature attained in the box type is medium (approx. 120 °C) [17] and very high in concentrating type (approx. 290 °C); however, indirect cooker has a high temperature but with a control option. Reprinted/adapted with permission from Ref. [18], 2018, Elsevier.

2.1. Direct Solar Cookers

Direct SCs are quite frequently used for cooking due to the small cost of materials and ease of construction. The two most common among them are box-type SC and concentrating SC.

2.1.1. Box-Type Solar Cookers

Box-type SC consists of single or multiple glasses covers over an insulated container. The container is painted black on the inside to maximize heat absorption. Norms behind the working of SC is the greenhouse effect, wherein the container is transparent to the small wavelength radiation but opaque to the longer wavelength radiation from hot objects and the heating effect is created due to the longer wavelength radiations. A box-type SC can consist of four cooking vessels inside the box. The schematic of the box-type SC is shown in Figure 2. In recent years, much technological advancement has improved the design and working efficiency of box-type SCs. The box-type SCs come in several modifications. In recent years, several solar cookers have been developed that come with and without reflectors (single, double, three, four, or even eight).

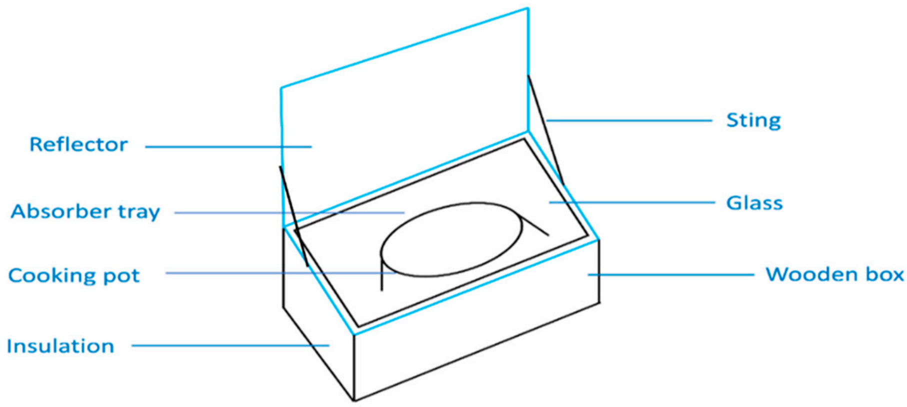

Figure 2. Schematic of box-type solar cooker.

The key reasons for the preference for box-type solar cookers over other cooker types are that they are user-friendly, easy to build, easy to use and operate, safe, and require little attention. They employ both direct and diffused solar radiation and do not require constant tracking of the sun. However, the main disadvantage of box-type SC is the long hours of cooking. Heat losses make these cookers challenging to operate in off-sunshine hours and windy conditions. They cannot generate high temperatures and so cannot be used for frying and roasting [19–21].

2.1.2. Concentrating Solar Cookers

Concentrating solar cookers employ optics to concentrate the sunrays on the receiver of the cooking unit, where they generate a very high temperature. It typically uses a parabolic concentrator, a cooking vessel at the center, and a stand with adjustable support so that the concentrator faces the sun, as represented in Figure 3.

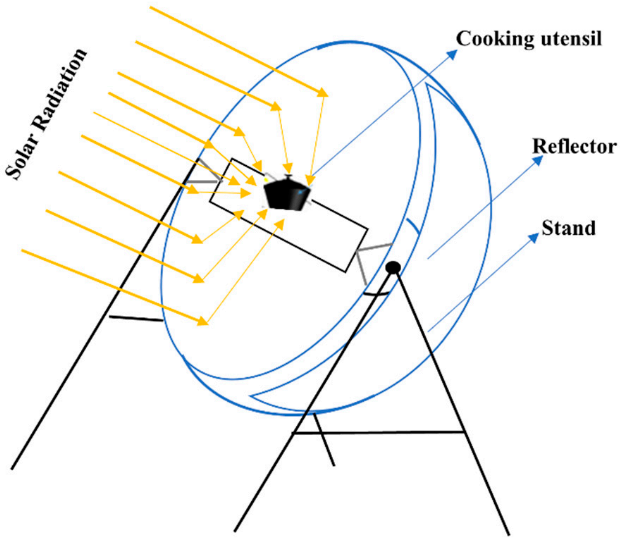

Figure 3. Concentrating solar cooker.

In concentrating SC, the temperature is very high, which is suitable for frying, baking, boiling, and roasting. With parabolic dish cookers, the temperature reaches between 350 °C and 400 °C. The cooking can be achieved in a short period. The major disadvantage of concentrating cookers is their cost, size, and risk of fire and burns. It also involves continuous tracking of the sun and careful attention to prevent food burning [18]. A particular type of lens called the Fresnel lens has been used as it can concentrate sunlight precisely to a focused area and can be made from plastic, sustaining wear and tear for long durations against UV rays and abrasions.

A Fresnel lens of 0.90 m × 1.20 m and 2 mm can concentrate sunlight 1229 times [22]. Although for high temperatures initially, Schaeffer Concentrator [23] was used, which needed a rotation mechanism for focusing sunrays, Fresnel lens application in fixed stoves provided a simple solution for high temperature applications.

2.2. Indirect Solar Cookers

The indirect solar cookers utilize thermal heat from the heat-transfer fluid, such as thermal oils and molten salts, which come from the focus point of the reflector. This heat is then transported to cooking vessels for cooking purposes. For indirect SCs, the heat collection and cooking sections are separated. The heat collection unit is placed outside or on the roof, while the cooking unit is inside or in the kitchen. Various types of collectors, such as flat-plate collectors or parabolic-trough collectors, are used for heat collection, as presented in Figure 4.

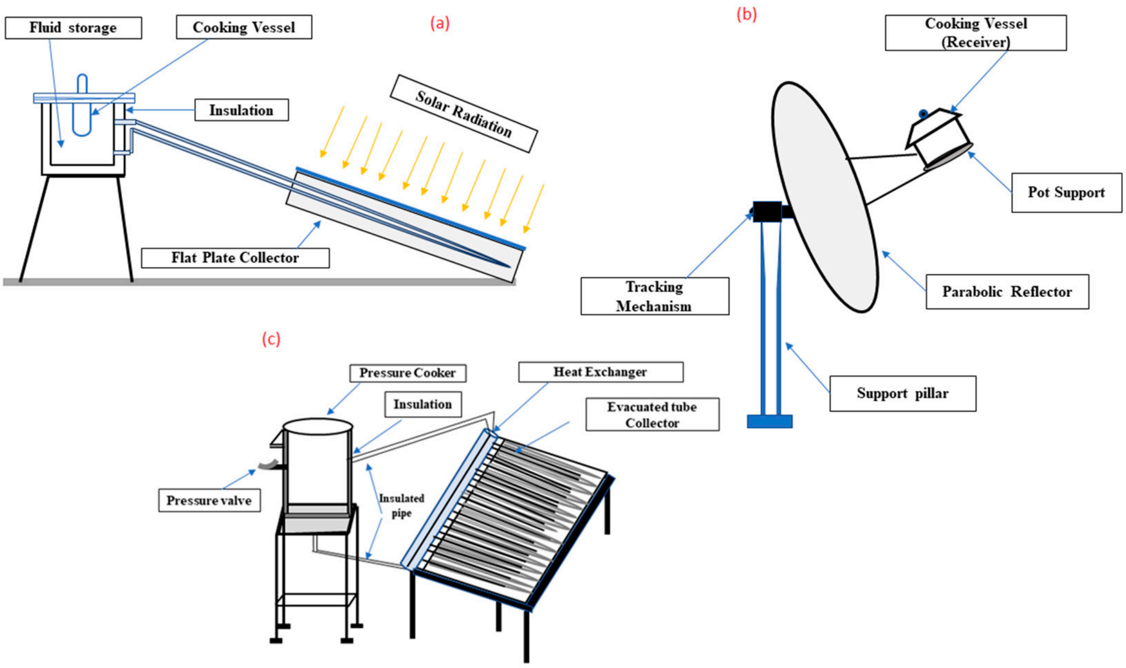

Figure 4. Indirect solar cooker types: (**a**) Flat-plate collector; (**b**) Parabolic collector; (**c**) Evacuated tube collector.

The main advantage of indirect SCs is that they can be easily integrated with a thermal energy storage unit that promotes cooking during off-sunshine hours. The cooking unit is placed indoors, so the food remains hygienic and free from dirt and contamination. These cookers can operate from intermediate to high-temperature ranges suitable for frying meat and cooking vegetables. However, the major disadvantage of these cookers is heat loss from the thermal transfer fluid while carrying heat from the collection unit to the cooking unit. The construction of these cookers is expensive and difficult to operate and maintain [24].

3. Performance Evaluation of Box-Type Solar Cookers

The performance evaluation of the SC can be undertaken by calculating the first (F_1) and the second figure of merit (F_2) according to criteria set by the Bureau of Indian Standards (BIS).

The F_1 can be calculated by obtaining the stagnation temperature of the cooker at no load state. It is the ratio of the optical efficiency, which can be equated with the rise in temperature of the absorber plate to the heat loss factor. This is mathematically represented as [25–27]:

$$F_1 = \frac{\eta}{U_{LS}} = \frac{T_b - T_a}{H} \tag{1}$$

Where η is the optical efficiency, U_{Ls} is the heat loss factor, T_b is the stagnation temperature of the absorber plate, T_a is the ambient temperature, and H is the solar radiation when the steady conditions are reached.

F_2 can be obtained in the full load condition using 2 kg of water, which is heated and boiled. The F_2 can then be calculated by measuring the ambient temperature, water temperature, solar radiation, and wind speed. This can be mathematically calculated as [27,28]:

$$F_2 = \frac{F_1 m_w c_{pw}}{A\tau} \ln \frac{\left[1 - \frac{T_{w1} - T_a}{F_1 \overline{H}}\right]}{\left[1 - \frac{T_{w2} - T_a}{F_1 \overline{H}}\right]} \tag{2}$$

where m_w is the mass of water, C_{pw} is the specific heat of water, A is the aperture area of SC, T_{w1} is the lower level of water temperature, T_{w2} is the upper level of water temperature,

τ is the time interval when the temperature of water rises from T_{w1} to T_{w2}, and $\overline{H}$ is the average solar radiation of water temperature rise from T_{w1} to T_{w2}.

The average power delivered by the cooker during the boiling process can be obtained by the below equation [28]:

$$P = \frac{m_{wC_{pw}}(T_{w2} - T_{w1})}{\tau} \quad (3)$$

4. Energy and Exergy Analysis for Box-Type Solar Cookers

4.1. Heat Transfer in a Box-Type Solar Cooker

For a simple SC with one flat cover glass, internal walls, and a thermal insulator pot that contains product for cooking, the heat transfer can be understood with the help of the following sample model in Figure 5. Furthermore, the energy and exergy analysis can be carried out based on the temperature of the load achieved in the pot in this sample cooker. The temperature calculations have been done in detail in the research [29]; however, only a sketch has been elaborated for easy comprehension.

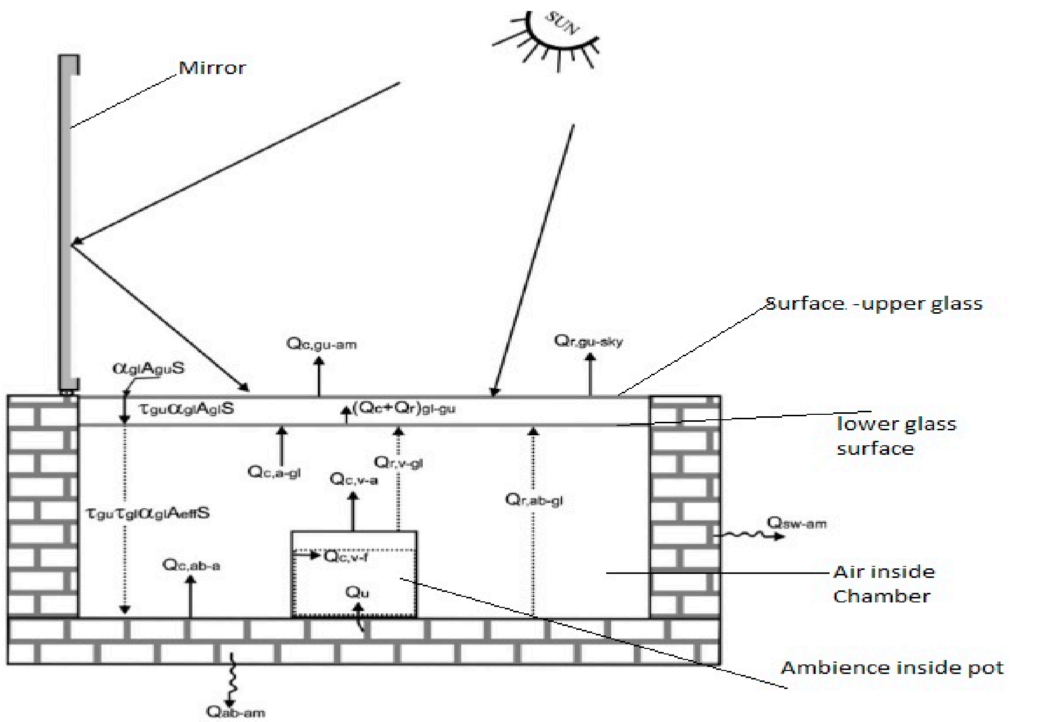

Figure 5. Sketch of a sample solar cooker with heat transient surfaces labeled. Reprinted/adapted with permission from Ref. [29], 2013, AIP Publishing.

The energy balance equation for the upper surface where sunlight is directly exposed as:

$$(MC_p)_{gu}\frac{dT_{gu}}{dt} = \alpha_{gu}A_{gu}S + (Q_c + Q_r)_{gl-gu} - Q_{c.gu-am} - Q_{r.gu-sky} \quad (4)$$

where

$$Q_{c;gl-gu} = h_{c,gl-gu}A_{gu}\left(T_{gl} - T_{gu}\right) \quad (5)$$

$$Q_{r;gl-gu} = h_{r;gl-gu}A_{gu}\left(T_{gl} - T_{gu}\right) \quad (6)$$

$$Q_{c;gu-am} = h_{c,gu-am}A_{gu}(T_{gu} - T_{am}) \quad (7)$$

$$Q_{r;gu-sky} = h_{r,gu-sky}A_{gu}\left(T_{gu} - T_{sky}\right) \quad (8)$$

The heat transfer equations for all the surfaces after combining individual expressions have been detailed as follows:

1. For energy balance at the upper glass surface:

$$(MC_p)_{gu}dT_{gu}/dt = \alpha_{gu}A_{gu}S + \left(h_{r,gl-gu} + h_{c,gl-gu}\right)A_{gu}\left(T_{gl} - T_{gu}\right) - h_{c,gu-am}A_{gu}(T_{gu} - T_{ma}) - h_{r,gu-sky}A_{gu}\left(T_{gu} - T_{sky}\right) \quad (9)$$

2. For sun radiation available on the upper glass aperture surface:

$$S_o = I_G + I_b F_{mr} A_{mr} Cos\ \phi \quad (10)$$

3. For energy balance at the lower glass surface:

$$(MC_p)_{gl}dT_{gl}/dt = \tau_{gu}\alpha_{gl}A_{gl}S + h_{c,a-gl}A_{gl}\left(T_a - T_{gl}\right) + h_{r,vc-gl}nA_{vb}\left(T_v - T_{gl}\right) + h_{r,ab-gl}(A_{gl} - nA_{vb})\left(T_{ab} - T_{gl}\right) - \left(h_{r,gl-gu} + h_{c,gl-gu}\right)A_{gl}\left(T_{gl} - T_{gu}\right) \quad (11)$$

4. For inside the vessel/pot and net energy balance for the vessel/pot:

$$(MC_p)_v dT_v/dt = \tau_{gu}\alpha_{gl}\alpha_v A_{vb}Sn + U_{vb}nA_{vb}(T_{ab} - T_v) - h_{cv-f}nA_v\left(T_v - T_f\right) - h_{r,v-gl}nA_{vb}(T_v - T_{gl}) - h_{c,v-a}nA_v(T_v - T_a) \quad (12)$$

5. For energy balance at the absorber base:

$$(MC_p)_{ab}dT_{ab}/dt = \tau_{gu}\alpha_{gl}\alpha_{ab}A_{eff}S + h_{r,ab-gl}(A_{ab} - nA_{vb})\left(T_{ab} - T_{gl}\right) - h_{c,ab-a}(A_{ab} - nA_{vb})(T_{ab} - T_a) - U_{ab}A_{ab}(T_{ab} - T_{am}) - U_{sw}A_{ab}(T_{ab} - T_{am}) - U_{vb}nA_{ab}(T_{ab} - T_v) \quad (13)$$

6. For energy balance of air inside the chamber:

$$(MC_p)_a dT_a/dt = h_{c,ab-a}(A_{ab} - nA_{vb})(T_{ab} - T_a) + h_{c,vc-a}nA_v(T_v - T_a) - h_{c,a-gl}A_{gl}\left(T_a - T_{gl}\right) \quad (14)$$

4.2. Energy Analysis

The temperature achieved in the solar cooker can be calculated by the above-mentioned equations. So total energy received by the water kept in the pot of the above sample solar cooker when the temperature increased from T_{w1} to T_{w2} is given by [18]:

$$E_o = m_w C_{pw}(T_{w2} - T_{w1}) \quad (15)$$

The total energy supplied to the water kept inside the SC is given by:

$$E_i = \overline{H}_{exp}A(\Delta t_{exp}) \quad (16)$$

where $\overline{H}_{exp}$, is the average solar radiation during the experiment and Δt_{exp} is the time interval of the experiment.

Therefore, the efficiency of SC is described as the ratio of energy gained by water to the energy supplied to the water, and its formula is given by [25]:

$$\eta_E = \frac{E_o}{E_i} = \frac{m_w C_{pw}(T_{w2} - T_{w1})}{\overline{H}_{exp}A\ (\Delta t_{exp})} \quad (17)$$

4.3. Exergy Analysis

Exergy is the qualitative aspect of energy, defined by the thermodynamic laws as the maximum amount of work that can be derived from any thermal system. The efficiency based on the idea of exergy is the true measure of the thermal performance of the thermal system [19].

The thermal exergy (ϵ) of water kept in the pot of the above sample solar cooker at a temperature of T_{w1} can be given by:

$$\epsilon_{Tw1=m_w}C_{pw}\ (T_{w1} - T_a) - T_a ln\frac{T_{w1}}{T_a} \quad (18)$$

When the temperature of the water rises from T_{w1} to T_{w2}, the exergy gain ($\Delta\epsilon_w$) can be given by:

$$\Delta\epsilon_w = \epsilon(T_{w2}) - \epsilon(T_{w1}) \quad (19)$$

Therefore, the exergy output (Θ_o) from the SC is defined as:

$$\Theta_o = \frac{m_w C_{pw}\left[(T_{w2} - T_{w1}) - T_a In\frac{T_{w2}}{T_{w1}}\right]}{\Delta t} \quad (20)$$

The exergy available via the beam and the diffused component of the solar radiation can be found by superposition and can be expressed as:

$$\Theta_{in} = I_b\left(1 - \frac{4T_a}{3T_s}\right) + I_d\left(1 - \frac{4T_a}{3T_s}\right) \quad (21)$$

The exergy input (Θ_{in}) to the solar cooker can be expressed as:

$$\Theta_{in} = I_s\left[1 - \frac{4T_a}{3T_s} + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right]A \quad (22)$$

where I_b is the beam solar radiation, I_d is the diffused solar radiation, T_s is the surface temperature of the sun, and I_s is the solar radiation.

The exergy efficiency (Ψ) of the SC is described as the ratio of output exergy (due to the rise in the exergy of water due to a rise in temperature) to the input exergy and given as [19,30]:

$$\Psi = \frac{Output\ exergy\ (\Theta_o)}{Input\ exergy\ (\Theta_{in})} = \frac{\frac{m_w C_{pw}\left[(T_{w2} - T_{w1}) - T_a In\frac{T_{w2}}{T_{w1}}\right]}{\Delta t}}{I_s\left[1 - \frac{4T_a}{3T_s} + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right]A} \quad (23)$$

5. Economic Analysis

5.1. Payback Period

The economic analysis of the SC is undertaken in terms of the amount of money it can save while using the solar cooker in place of the LPG. This saving is then utilized to calculate the payback period, which is the time taken to recover the initial investment. To calculate the payback period, the amount of savings is first calculated, which can be given by the following equation [18]:

$$SPM = P_r \cdot M_{LPG} \cdot C_{LPG} \quad (24)$$

Where, SPM is the saving per month, Pr is the percentage of time LPG is used, M_{LPG} is the mass of LPG consumed per month, and C_{LPG} is the cost of LPG per kg.

Therefore, the payback period (PP) can be found as [31]:

$$PP = \frac{Total\ cost\ of\ the\ cooker}{SPM} \quad (25)$$

5.2. Net Present Value (NPV)

NPV is used to evaluate the viability of any investment in a project. It is the difference between all the present values of the cash inflow and the cash outflow during a time period. The positive and large value of NPV is desirable for investment. The greater the value of

NPV, the more profitable is the project, which can bring more significant returns. The NPV is given by the following equation [21,32]:

$$NPV = (C_{a,m} \; - C_{O\&M})[\frac{(1+d)^n - 1}{d(1+d)^n}] + \frac{C_{sc}}{(1+d)^n} - C_{i,sc} \quad (26)$$

Where $C_{a,m}$ is the yearly savings, $C_{o,m}$ is the operation and maintenance cost, C_{sc} is the salvage value of the box-type SC, $C_{i,sc}$ is the capital cost, d is the discount rate, and n is the number of years.

5.3. Benefit–Cost Ratio (B–C Ratio)

The B–C ratio is an essential parameter for the financial well-being of a project. The value of all the benefits from a project in monetary terms should be greater than all the costs to have a financially viable project. This means that the value of B–C should be greater than one. The mathematical expression of the B–C ratio can be given by [32]:

$$B - C = \frac{C_{a,m}\left[\frac{(1+d)^n - 1}{d((1+d)^n}\right] + \frac{C_{s,c}}{(1+d)^n}}{C_{o,m}\left[\frac{(1+d)^n - 1}{d((1+d)^n}\right] + C_{i,sc}} \quad (27)$$

5.4. Internal Rate of Return (IRR)

IRR is the discount rate at which NPV becomes zero. The higher the value of IRR, the more attractive is the investment. It is estimated using the following equation [32]

$$NPV = 0 = (C_{a,m} \; - C_{O\&M})[\frac{(1+IRR)^n - 1}{IRR(1+IRR)^n}] + \frac{C_{sc}}{(1+IRR)^n} - C_{i,sc} \quad (28)$$

5.5. Levelized Cost of Heat (LCOH)

LCOH is the cost of heat generated by the thermal system, which helps to compare different thermal technologies for heat and power generation. It depends on locations, technologies, receivers, and other economic parameters. The LCOH is calculated in $/kWh. It is given by [25]:

$$LCOH = \frac{C_{i,sc} + \sum_{t-1}^{n} \frac{C_{o,m}}{(1+r)^t}}{\sum_{t-1}^{n} \frac{E_t}{(1+r)^t}} \quad (29)$$

where E_t is the energy saved.

The energy produced by the solar cooker can be given by the following expression [25]:

$$\begin{aligned} &Energy\ produced\ by\ the\ solar\ cooker \\ &\quad = Solar\ radiation\ \left(\frac{kWh}{m^2}\right) \times aperture\ area\ of\ the\ cooker\ \left(m^2\right) \\ &\quad \times efficiency\ of\ the\ solar\ cooker\ (\%) \end{aligned} \quad (30)$$

5.6. Levelized Cost of Cooking a Meal (LCCM)

LCCM is a crucial constraint for the economic analysis of a solar cooker. It is a frequently used model by energy practitioners to assess the different cooking solutions according to the different accepted metrics. The mathematical expression of the LCCM can be given by [25,26]:

$$LCCM = \frac{C_{i,sc} + \sum_{t-1}^{n} \frac{C_{o,m}}{(1+r)^t}}{\sum_{t-1}^{n} \frac{Ml_t}{(1+r)^t}} \quad (31)$$

where Ml_t is the amount of the meal cooked per year.

6. Environmental Analysis

The environmental analysis of solar cookers can be performed regarding the amount of CO_2 emissions it can inhibit from going into the environment. The CO_2 emitted from the traditional cooking method that uses liquefied petroleum gas (LPG) composed of propane and butane can be quantified using the following stoichiometric calculation:

$$C_3H_8 + 5(O_2 + 3\ .76\ N_2) = 3CO_2 + 4H_2O + 18.8N_2$$

$$2C_4H_{10} + 13\ (O_2 + 3.76\ N_2) = 8CO_2 + 10H_2O + 48.88N_2$$

The calculation shows that for each 1 kg of propane and butane burnt, 3 kg to 3.0345 kg of CO_2 are released into the environment. To analyze the environmental effect of cooking, a study was undertaken by Herez et al. [18] to quantify the amount of CO_2 generated from cooking at home, at a snack bar, at a hotel, and in a restaurant. The result of the study is shown in Table 1. The estimates showed that 60.55, 908.28, 3996.43, and 6055.20 kg CO_2 is generated per month in a typical home, snack bar, hotel, and restaurant, respectively.

Table 1. Quantity of CO_2 released into the environment from the LPG. Reprinted/adapted with permission from Ref. [18], 2018, Elsevier.

	Quantity of LPG (kg/Month)	Quantity of Propane (kg/Month)	Quantity of Butane (kg/Month)	Quantity of CO_2 Generated from Propane (kg/Month)	Quantity of CO_2 Generated from Butane (kg/Month)	Total Quantity of CO_2 from LPG (kg/Month)
Home	20	4	16	12	48.55	60.55
Snack	300	60	240	180	728.28	908.28
Hotel	1320	264	1056	792	3204.43	3996.43
Restaurant	2000	400	1600	1200	4855.20	6055.20

The amount of CO_2 that can be reduced using a box-type solar cooker can be calculated using the following equation [18]:

$$Q_{red,CO_2} = P_r \cdot Q_{total,CO_2} \quad (32)$$

where Q_{red,CO_2} is the quantity of CO_2 reduced while using a box-type SC in place of a conventional LPG, Q_{total,CO_2} is the total quantity of CO_2 produced (in kg/month) when using conventional LPG, and P_r is the percentage of the time a solar cooker is used.

Here, it is important to note that 30.27, 454.14, 1998.21, and 3027.6 kg/month of CO_2 can be reduced at home, snack bar, hotel, and restaurant if the SC is used 50% of the time. When the SC is used the whole time, 60.55, 908.28, 3996.43, and 6055.20 kg/month of $CO_{2,}$ respectively, can be prevented from releasing into the environment. It is important to note that the fuel used in calculating CO_2 reduction is LPG, which is not universal. Many countries use natural gas as an option, and similar calculations can be shown against natural gas or any other gas used as fuel to calculate the quantity of reduced CO_2.

7. Box-Type Solar Cooker without Thermal Energy Storage

Box-type SC is shaped in the form of a box with insulation in one or multiple layers in the form of glass covers and side plates, so that with the greenhouse effect, heating can be generated, and this heat can be used for cooking. Initially, the solar cooker was made of a simple box with wooden walls and a glass lid, in which the cooking vessel was kept, and the bottom plate was made of insulating material. Subsequently, as a design improvement, a reflector with a hinge joint was added to one edge of a wall to reflect solar radiation and increase the amount of radiated heat on the receiver. Afterward, multiple reflectors were added to the box to escalate the amount of solar radiation and to enhance direct solar radiation; a mechanism of movement of the reflector was also added. Further, the number of reflectors increased from four to six and more in the form of a multi-faced cone which can direct more radiation to the vessel. So, development has been done by adding multiple glass panels and reflectors, starting with the simple box solar cookers. This continuous improvement in the initial design has been carried out over the years to increase in situ heat content. A systematic development for improving solar cookers [8] is detailed in Figure 6.

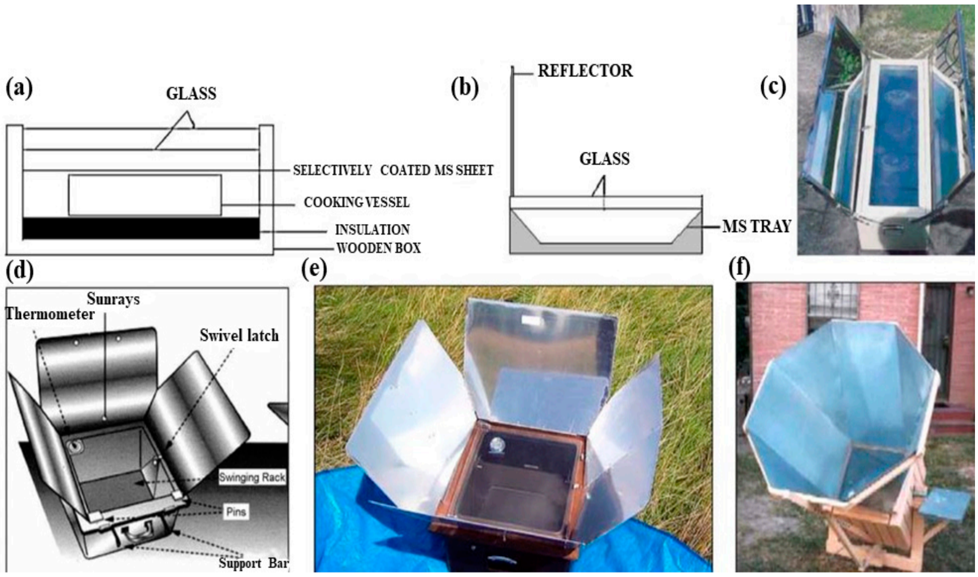

Figure 6. Pictures of solar cooker developed: (**a**) Simple box with glazed glass lid and insulated bottom; (**b**) Single-reflector box-type solar cooker; (**c**) Twin-reflector solar cooker; (**d**) Simple four-faced-reflector solar cooker; (**e**) Four-faced-reflector solar cooker with Swinging rack; (**f**) Multi-faced conical reflector solar cooker. Reprinted/adapted with permission from [8], 2010, Elsevier.

Harmim et al. [16] experimented with a box-type SC by mounting fins for heat transfer and compared the difference between experiments with and without fins. The main reason for this study was to explore the possibility of reducing cooking time by a simple modification and changing the geometry of the box design. The use of fins noticed more heat transfer, and it was found that the base plate equipped with fins had a stagnation temperature of more than 7% as compared to the ordinary base plate. Using fins reduced the time taken to boil sample water, and the same water boiled in less time (by 12%) for the case with fins as compared to the case without fins. So, it was observed that fins played a significant role in heat transfer for box cookers, and accordingly, it was recommended for future designs. The sketch of the experiment and pictures of the actual set-up and the finned plate is shown in Figure 7.

Harmim et al. [33] designed a box-type SC with an asymmetric parabolic concentrator with two opposite surfaces to focus solar energy directly on the box. The experiment set picture is enclosed in Figure 8. Based on the thermal simulation analysis, it was found that evening cooking can also be conducted with this CPC setup, and the same was validated by the study of the cooker performance, rated using the first and the second figures of merit. The solar cooker design had insulation on the double-glazed box walls, and the two reflectors were placed so that all the sunlight was directed to a transparent glass beside which a plate for heat absorption was placed.

Harmim et al. [34] developed a novel SC that could be installed into a building along with the reflectors and did not need sun-tracking. The design was constructed using in-house items detailed in Figure 9. Various tests were conducted without any load during extreme seasons, and the temperature achieved was 166 °C and 165 °C in the summer and winter seasons, respectively. Furthermore, the temperature reached without a reflector was 127.7 °C during winter. The power rating noted during the experiment was 78.9 W.

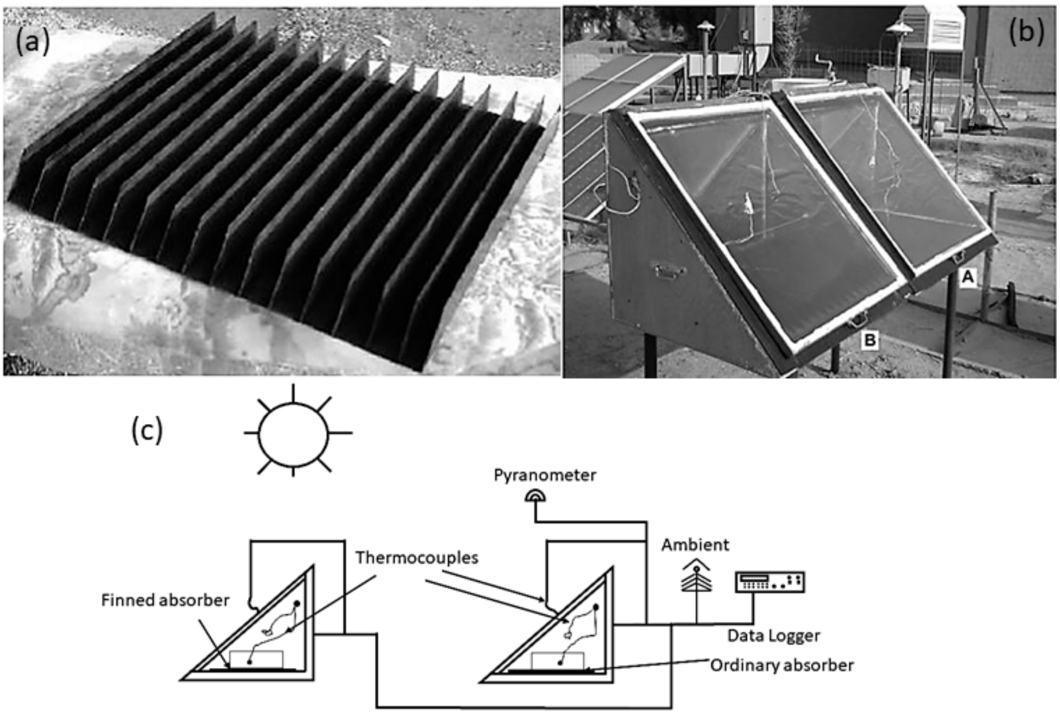

Figure 7. (**a**) Fins of the base plate of solar cooker; (**b**) Actual experiment set; (**c**) Schematic diagram of experiment. Reprinted/adapted with permission from Ref. [16], 2010, Elsevier.

Misra and Aseri [35] used convection in heating the box-type solar cooker vide an experiment in which a fan was placed in situ with the pot. The experiment results bestowed that there was a significant improvement in the thermal performance of box-type SC by applying the convention. Further, there was also a considerable reduction in the cooking time, about 30.6%.

Folaranmi [36] made an SC with double glazing along with a reflector. The box-type SC used for the experiment had an aluminum absorber plate painted matt black. The bottom and sides were covered with fiberglass and insulated with wool with a 50 mm thickness and a value of k as 0.052 W/m°C. As a result of the experiment, it was evident that a non-tracking solar concentrator could give efficient heating for cooking by improving upon significant heat collection.

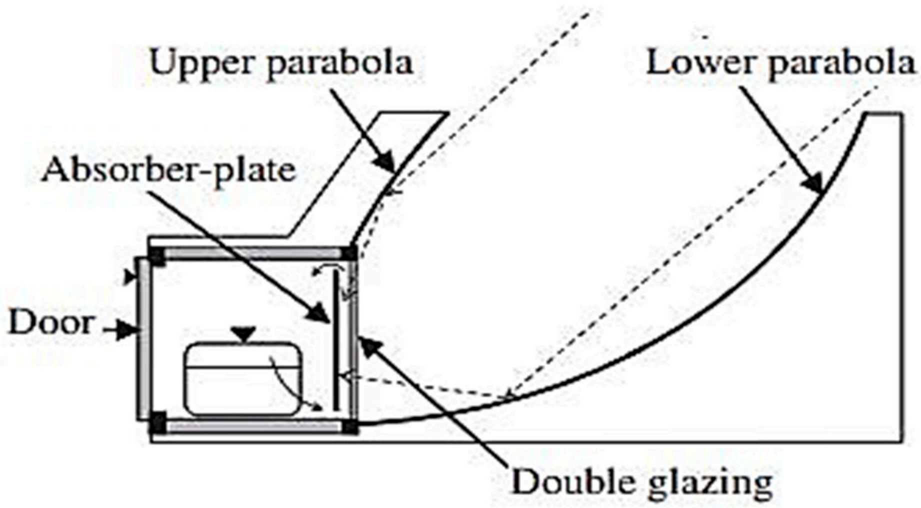

Figure 8. *Cont.*

Figure 8. Schematic diagram of the box-type solar cooker with CPC and actual photograph. Reprinted/adapted with permission from Ref. [33], 2012, Elsevier.

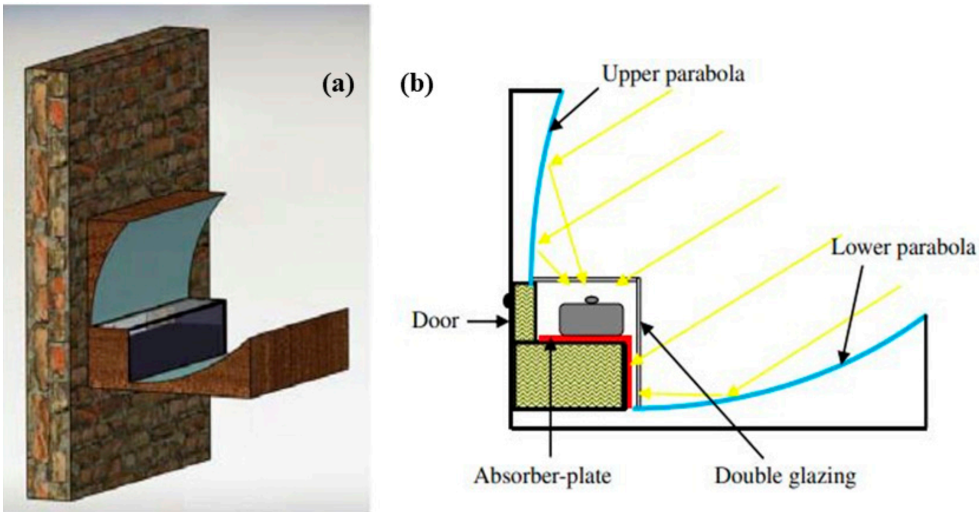

Figure 9. (**a**) SC unified into a building wall; (**b**) Schematic diagram of a solar cooker in asymmetric line. Reprinted/adapted with permission from Ref. [34] 2013, Elsevier.

A long-term experiment was conducted by Soria-Verdugo [37] in various countries. A calculation of convective coefficients for various components of the solar cooker was made via a heat transfer model. The solar cooker was used at various locations in different countries, and the number of days when the temperature was more than 100 °C was summed up for analysis. Further, a calculation for the amount of wood saved by the use of this setup was done. Based on the outcome of experimental data, it was evident that as an alternative to wood, solar radiation-based cooking had a high perspective, especially for developing countries.

Mahavar et al. [38], in 2015, developed a lightweight, small size, convenient design, budget polymeric glaze single-family solar cooker (SFSC) weighing only 0.8 kg (Figure 10). The cooker was tested under different conditions around the year on different days, and specific performance parameters were calculated. The values of the first and the second figures of merit indicated that SC could provide afternoon and evening cooking on the same sunny day. The standard parameters for assessing a solar cooker, such as cooking power at various temperature differences and coefficient of heat loss, were compared with many benchmark models, and the value was found to be better. Year-long good solar cooker performance was achieved by cooking several food items around the year. Based on the study, such a glazed solar cooker could be recommended for cooking consecutive meals on sunny days for a small family of two people.

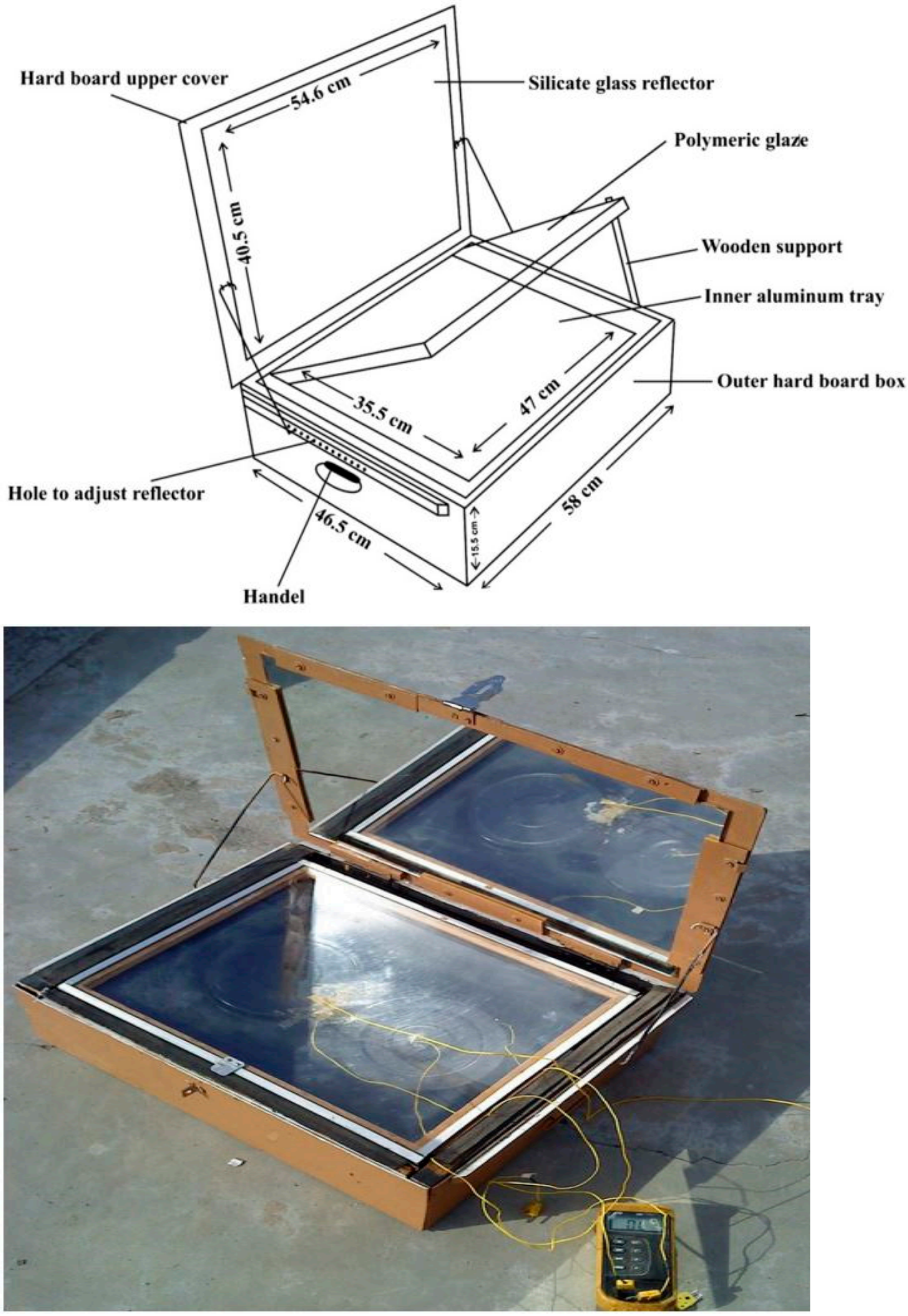

Figure 10. Schematic diagram of solar cooker SFSC. Reprinted/adapted with permission from Ref. [38], 2012, Elsevier.

Saxena and Agarwal [39] developed a unique new box cooker (Figure 11) integrated with a trapezoidal duct and convective heating. The purpose was to augment the rate of heat transmission and to reduce the cooking time and efficient heat utilization in an environment of low ambient heat conditions. Convective heating was done through a

200 W halogen lamp attached at one end of the trapezoidal duct, and a forced convection air heating was given by a 10 W fan placed at the small cross-sectional end of the trapezoidal duct. Further, numerous small hollow balls of copper were placed inside the chamber, where hot air was blown, and sunlight was focused on the heating. These hollow copper balls became heated and helped to enhance heat transfer, thereby improving thermal performance. Tests were conducted to calculate the standard parameters of performance of any SC, such as thermal efficiency, figures of merit (F_1 and F_2), etc., and encouraging results were found. The use of a concentrator along with a solar cooker gave thermal efficiency of 45.11%, which is better than SC without a concentrator.

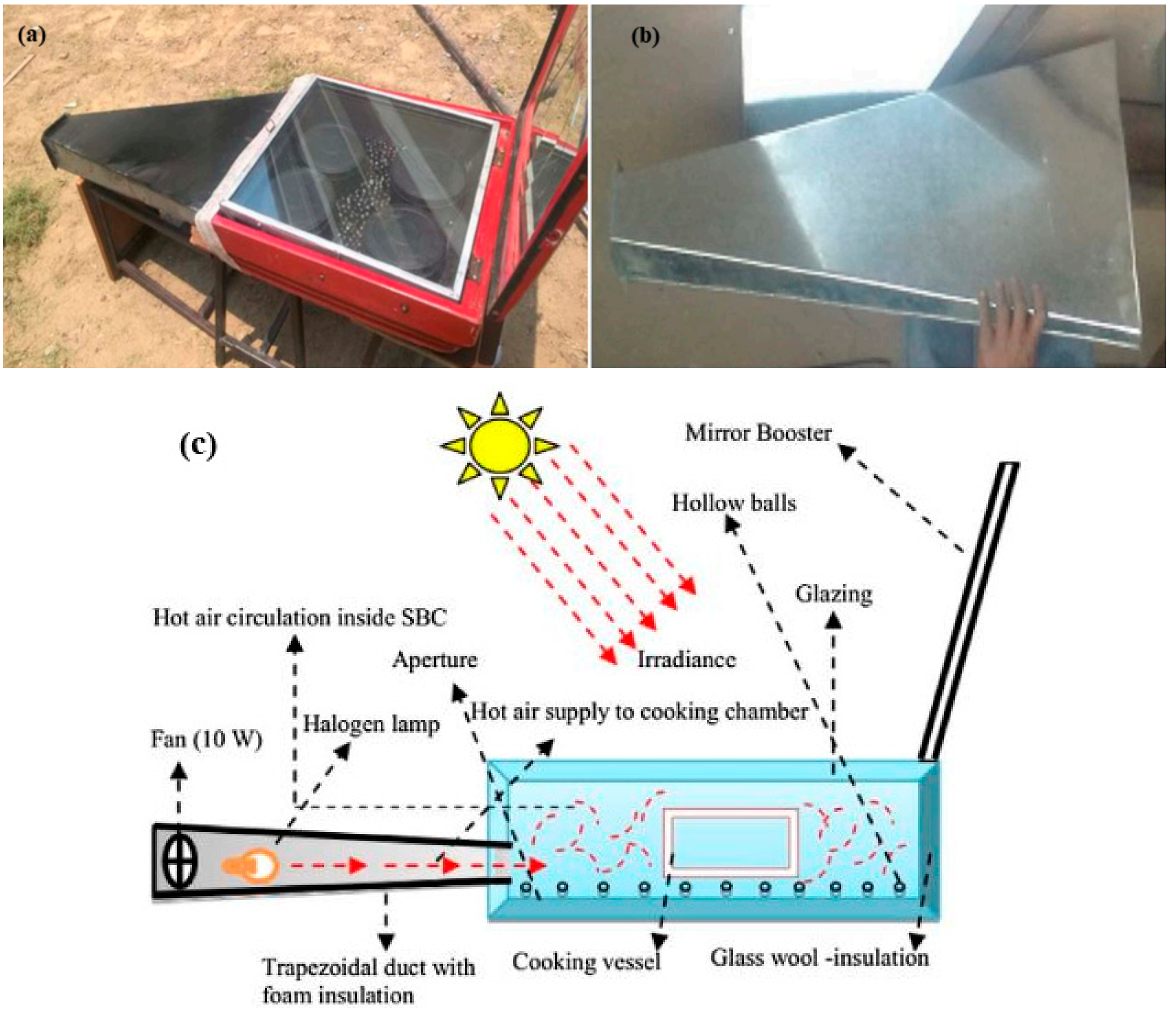

Figure 11. (**a**) Experiment set up; (**b**) Modified duct; (**c**) Schematic diagram of modified SBC. Reprinted/adapted with permission from Ref. [39], 2018, Elsevier.

Kolhe et al. [40] experimented with an octagonal box-type SC based on focusing sun-rays on the vessels directly with eight reflecting surfaces. The edges of the mirror form an octagonal (Figure 12) whose length was calculated through trigonometric computation, and, accordingly, the area of the bottom octagon was achieved. The basic reflection principles were used for calculating the angle for collecting the maximum amount of sun rays. Many experiments were done for calculating various thermodynamic analyses, and the parameters calculated were as follows: the first figure of merit as 0.3027; the second figure of merit as 0.607; the power of cooking as 19.767 W., and efficiency as 38.36%. An octagonal design was used to achieve more heat in the focused area concerning simple SC developed to date. With more reformed octagonal SC, an increase in cooking power of 23.52% and an increase in efficiency of 26.55% were achieved. Further, the heating rate achieved by this geometric modification was higher than in old conventional designs.

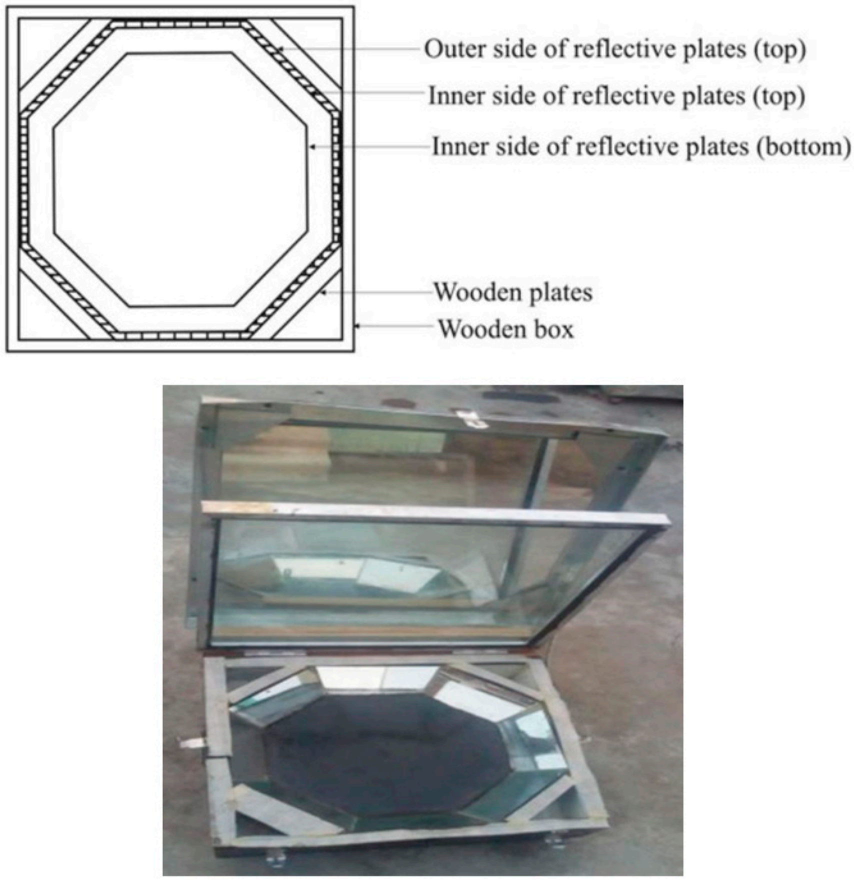

Figure 12. Schematic diagram and photograph of the solar cooker with Octagonal. Reprinted/adapted with permission from Ref. [40], 2019, Springer Nature.

Engoor et al. [41] did a comparison study using a Fresnel lens magnifier (Figure 13) and calculated the difference in power enhancement for the magnifier cases with and without a lens, respectively. With the Fresnel lens, there was an increase in cooking power noticed from 43.83 W to 46.87 W, against a temperature difference of 50 °C. Overall parameters were found to improve with magnifiers, such as concentration, the ratio increased by 48.7%, and energy efficiency increased from 29.6% to 32.4%. So, it was concluded that the Fresnel lens magnifier could increase the overall efficiency of a typical SC.

Khallaf et al. [42], in 2020, developed a novel design SC (Figure 14) named Quonset solar cooker (QSC). The cooker body was configured with internal reflectors in two chambers for double cooking. The overall perspective of designing QSC was to design and fabricate an SC for use in low and intermediate-temperature cooking, and accordingly, thermal analysis was also carried out. Further, a mathematical model was offered to validate thermal analysis through parametric analysis. A proper agreement between the experiment and the mathematical model was achieved, based on which it was submitted that Quonset SC could be used for cooking successively during the day. It was found that Quonset solar cooker with water gave 6–35% efficiency and with glycerin 9–92% efficiency.

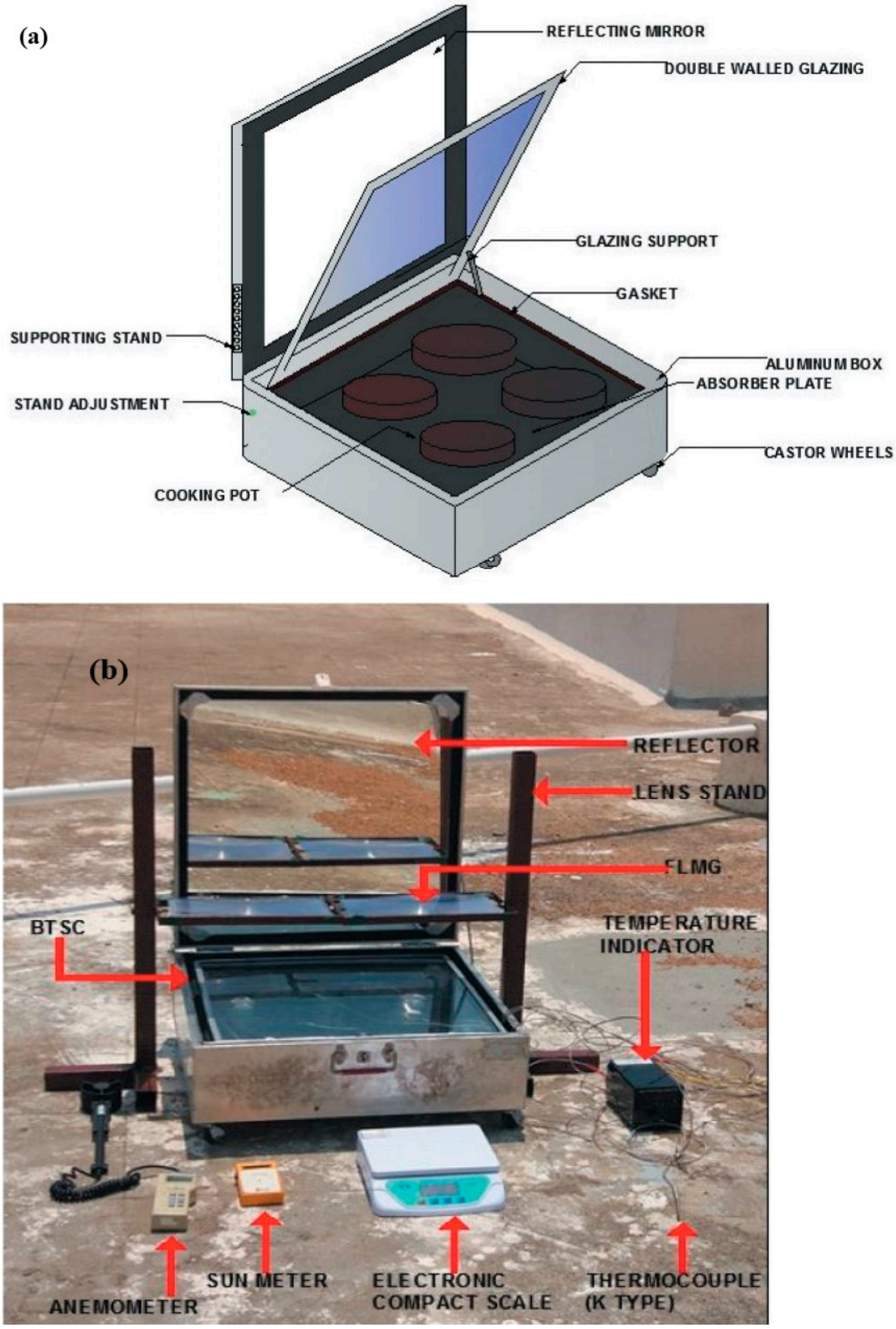

Figure 13. (**a**) Components of box-type solar cooker; (**b**) Experimental setup Mirror. Reprinted/adapted with permission from Ref. [41], 2020, Taylor & Francis online.

Hoigebazar and Valder [43] made a compound parabolic solar concentrator (CPC) (Figure 15) that focuses maximum sun rays on the subject pot till the incoming ray angle lies within the range of the acceptance angle of the CPC. The sole purpose of using CPC was to accumulate the distributed solar radiation energy and focus it on the receiver. Two configurations of the CPC were made, first, with a front area of 0.429 m^2, and second, with a front area of 0.385 m^2 against the same receiver area. The performance of the first CPC was found to be better for the same content. However, the comprehensive study concluded that the performance of SC with CPC was better than those without CPC.

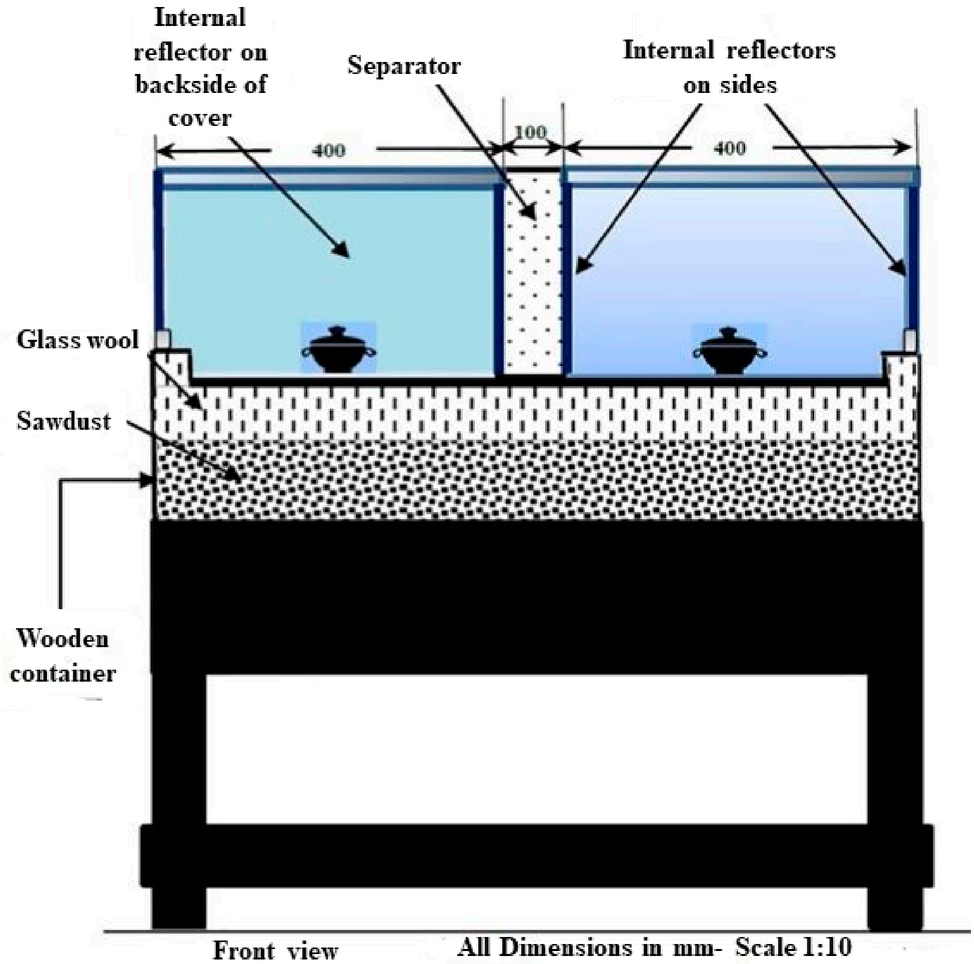

Figure 14. Schematic diagram of Quonset solar cooker (QSC). Reprinted with permission from Ref. [42], 2020, Elsevier.

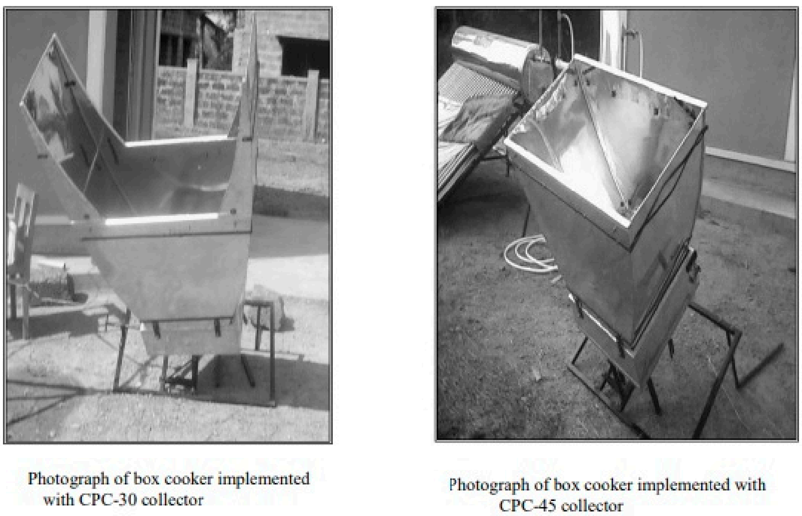

Figure 15. Box cooker with CPC Concentrator. Reprinted/adapted with permission from Ref. [43], 2020, AIP Publishing.

Terres et al. [44] studied the use of multiple reflectors on a box-type SC and demonstrated the cases by varying the angular position of the reflectors in experiments. About five reflectors were used for the experiment. The high value of the temperature was found when the angle of reflectors was inclined at 40°, 50°, 60°, 70°, and 81°, with the highest temperatures reaching 98.1 °C at an 81° inclination angle. Further, the low temperature was reported at reflector angles of 13°, 18°, 21°, 24°, and 30°, with the highest temperature value of 83.9 °C.

Vengadesan and Senthil [45] conducted different experiments to check the outcome of using fins on thermal transmission in solar cooking. Four types of covers, including those with or without fins (lengths 25 mm, 35 mm, and 45 mm fixed on covers for conducting tests, as shown in Figure 16), were used in the experiment. Water was used as the subject, and its peak temperature and time of reaching the highest temperature were checked. With a configuration of the fin height of 45 mm, the highest water temperature was noticed as 102 °C and the time duration for reaching a boiling point was 2 h and 17 min. Further, solar cookers with fins had a higher thermal performance due to increased heat transfer surface area than the conventional ones.

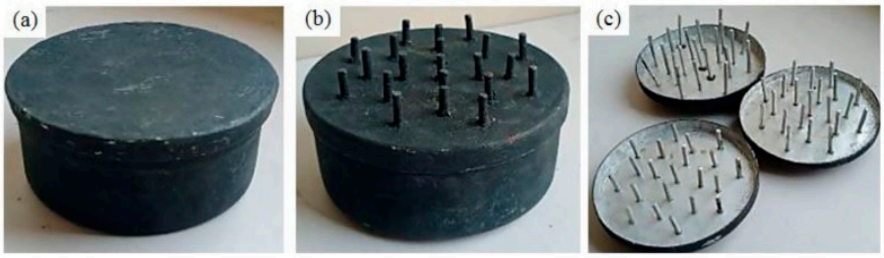

Figure 16. Diagram of fins of varying sizes used over vessels. (**a**) Without fins; (**b**) Finned cooking vessel; (**c**) Finned lids (inside view). Reprinted/adapted with permission from Ref. [45], 2021, Elsevier.

8. Box-Type Solar Cooker with Thermal Energy Storage Concept

Sharma et al. [46] reviewed various types of PCM used in various solar cooker designs. Starting from using sand by Ramadan et al. [47] with a small coat of salt hydrate $Ba(OH)_{2.}$ $8H_2O$ in an SC design to obtaining an overall energy conversion of 28.4% with pentaerythritol. Bushnell [48] achieved significant improvement with solid–solid transition employed for energy storage compared to solid–liquid transition. In an experiment, a non-TES system was compared to a system with PCM as pentaerythritol by Bushnell and Sohi [49]. This experiment was conceived for studying thermal energy retention periods, cooking extraction intervals, time duration, and efficiency. In another study, the feasibility of cooking with PCM during non-sunshine hours was tested experimentally with stearic acid (SA) magnesium nitrate hexahydrate (MNHH) by Domanski et al. [50]. The author discovered that the amount of the cooking medium, solar irradiation, and thermal–physical parameters of the phase change material affect cooker performance.

Buddhi and Sahoo [51] used stearic acid (commercial grade) in box-type SC and discovered it was many times more efficient than steam and heat-pipe SC. The results suggested that the application of PCM as a latent heat storage medium in solar cookers under India's composite climatic conditions is possible and that meals may be cooked even in the evening.

Belghit et al. [52] used acetamide (commercial grade) in a double-glazed box-type SC, where the PCM container was welded with eight fins to increase the heat transmission rate. It was found that three batches of food were cooked per day in the summer and two batches per day in the winter, respectively. As per the study, it was assessed that solar energy storage had no effect on the performance of SC for midday cooking.

Buddhi et al. [53] used acetanilide (commercial grade) with a double-glazed box-type SC with an opening area of 50 cm × 50 cm and a depth of 19 cm in an experimental study. In this study, PCM, Acetanilide (2.0 kg), was stored below the absorbing plate so that even if food ingredients were added late by 15.30 h, the second batch of food would be cooked with the same stored heat, even during the winter season. The test findings have shown that late-evening cooking was achievable in an SC with three reflectors. Further cooking experiments with 4.0 kg of PCM in two concentric aluminum chambers (Figure 17) with three reflectors in the storage unit were successful for evening cooking till 08:00 p.m.

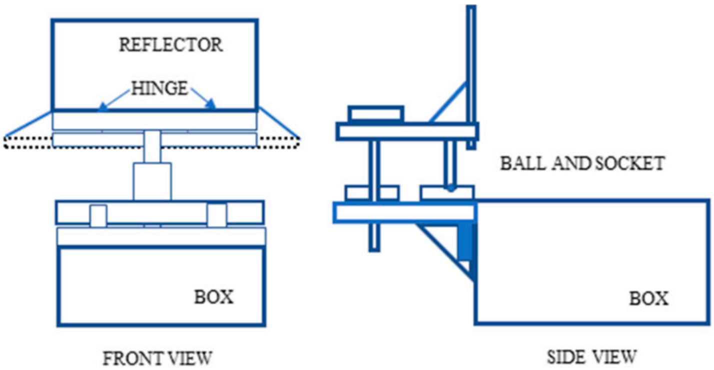

Figure 17. Ball and socket mechanism of right and left side reflectors. Reprinted/adapted with permission from Ref. [53], 2003, Elsevier.

There is a lot of research wherein the performance of the box SC was investigated under various operational and environmental settings. With Erythritol [54–56] as part of these studies, it was found that midday cooking had little effect on cooking during off-sunshine hours, while evening cooking with PCM as TES, was discovered to be quicker as compared to midday cooking. These studies and experiments revealed that, despite poor heat transfer, the prototype solar cookers performed satisfactorily in the existing arrangement, and the enhanced design of the heat exchanger in the TES storage unit would improve the thermal transmission rate.

Geddam et al. [57] conducted theoretical research with numerical calculations on PCM, such as magnesium nitrate hexahydrate, stearic acid, acetamide, acetanilide, and erythritol, for TES for box-type SC. In the numerical calculation of the heat exchanger container, several materials, such as copper, glass, stainless steel, aluminum, tin, and mixed aluminum, were considered. During the phase change process, the boundary wall temperature significantly impacted the melt fraction, which was not greatly affected by the initial PCM temperature. With varied heat exchanger container materials, stearic acid and acetamide were found suitable as PCM in a box-type SC for the preparation of food and keeping meals hot till late evening.

Yuksel et al. [55] used paraffin wax in a double-glazed box-type SC (Figure 18). In that experiment, 3.5 kg of paraffin wax was filled in the space clawed between aluminum plates and metal shavings. The reflector boosted thermal performance to roughly 18.35%. Metal shavings were capable of distributing heat evenly throughout the paraffin wax. The paraffin got a maximum temperature of 75.1 °C to 80.5 °C during the testing. The intended usable thermal efficiency of the SC ranged from 30.10% to 40%.

Tarwidi et al. [58] made mathematical modeling of the fourth numerical simulation of PCMs, such as erythritol, magnesium nitrate hexahydrate (MNHH), and magnesium chloride hexahydrate (MCHH), with SC with a solar heat collector. Godunov process was used in simulating the thermal evaluation of said PCMs. The solar thermal energy storage capacity of magnesium chloride hexahydrate was the greatest. Erythritol had maximum temperature history through the charging and the initial 54 min of discharge. After the charging time was through, erythritol as a heat storage medium was only suitable for a brief time; however, magnesium chloride hexahydrate was used for the late-evening cooking.

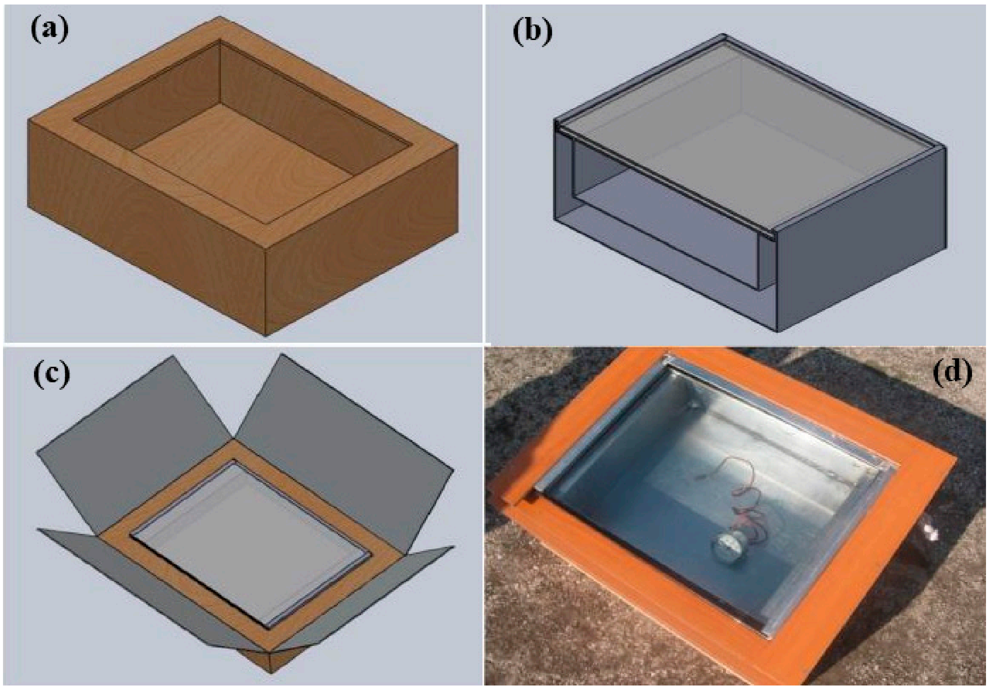

Figure 18. (**a**) Outer box; (**b**) inner box; (**c**) reflectors; (**d**) double-glazed conventional box-type SC. Reprinted/adapted with permission from Ref. [55], 2012, AIP Publishing.

Geddam et al. [57] used paraffin with box-type SC (with double exposure) having an area of 0.1344 m^2 with the aid of PCM medium in which meals prepared were maintained hot for 3–4 h. Various parameters, such as optical efficiency and heat capacity, which qualify a material for its construction, were discussed. Paraffin use as PCM material significantly improved as cooking time was consistently reduced when the box-type SC was used in conjunction with a finned cooking vessel.

Nayak et al. [59] used acetanilide and stearic acid SC with an evacuated tube solar collector (area 84 cm × 58 cm and height 58 cm) supplying a PCM storage unit in a closed-loop water line. PCM storage unit, stainless steel heat exchanger, cooking vessel, and the SC were found to cook effectively in the evenings till 7:30 p.m. At 3 p.m., the temperature of the PCM material had risen to above 120 °C, which was enough to cook the meal in the evening. From a performance standpoint, acetanilide would be preferred over stearic acid. With acetanilide as a PCM, a 30% cooker efficiency and 60 to 65% collector efficiency were reported.

Sharma and Rai [60] conducted an experimental study with magnesium nitrate hexahydrate in a box-type SC with two models. In both models, the same plate of surface area (0.75 m × 0.75 m) was used for absorption, which consists of galvanized iron sheet painted black, thereby increasing the capability toward the absorption of incoming solar radiation. Due to the space minimization and thermal inertial effect, the energy efficiency of Model II with fins attached was determined to be 439% higher than that of Model I, which was a simple cooking pot without fins. For Model II, the highest efficiency value was 70%, which was recorded at 12:30.

Further oxalic acid dehydrates were also used by Vigneswaran et al. [61] in direct box-type SC (Figure 19) with four reflectors. An experiment for cooking in a double-glazed, glass-covered solar cooker was conducted. As per energy requirements, the oxalic acid PCM required for cooking half a kg of rice was 2.9 kg. PCM storage unit consisted of two hollow concentric chambers designed from aluminum with diameters of 25.5 cm and 17.5 cm. The cooking research findings revealed that chosen PCM could deliver thermal energy effectively, with a discharge efficiency of 57%.

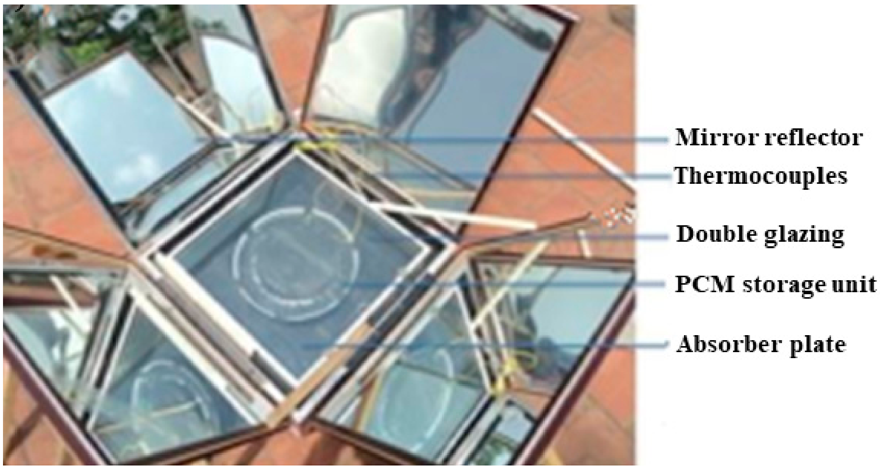

Figure 19. SBC with reflectors fabricated with PCM. Reprinted/adapted with permission from Ref. [61], 2017, AIP Publishing.

Hebbar et al. [62] used magnesium nitrate hexahydrate for designing an evacuated tube-powered SC in which a cooking pot was arranged in two concentric hollow cylinders of stainless steel, and the gap of the cylinder was packed with heat-transfer fluid (HTF). The HTF was heated directly in sunlight, and hot fluid would arise via a thermo-siphon cycle. This study focused only on the design and fabrication of an evacuated tube-based SC with a working fluid and PCM-based TES material.

Cocia et al. [63], in experimental validation, used a high-concentration ratio (10.78) SC, based (Figure 20) on a parabolic trough with Salt (53 wt.% KNO_3, 40 wt.% $NaNO_2$, 7 wt.% $NaNO_3$) in the range of 170–130 °C, placed in annular space between the pots. Four different test sets were conducted for a total of 14 tests in the heating and cooling phase, wherein thermal stabilization was found to improve with PCM significantly when sunrays were absent. Additionally, in the case when PCM was used, cooling took more time, about 65.12% to 107.98% higher compared to a case without PCM.

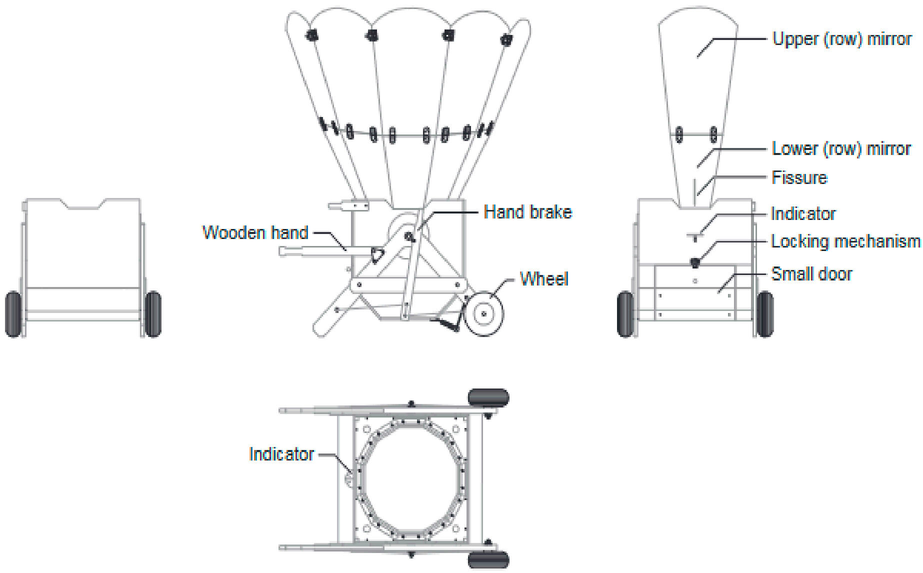

Figure 20. The layout of solar cooker with locking mechanism. Reprinted/adapted with permission from Ref. [63], 2018, Elsevier.

Coccia et al. [64] used erythritol (commercial grade-2.5 kg) in an SC experimental study using a portable box-type SC (Figure 21) with a 4.08 concentration ratio and thermal energy storage based on said PCM. When the solar source was unavailable or inconsistent, the inclusion of the erythritol-based thermal energy storage helped to stabilize and prolong the usage of portable box-type SC. Testing was carried out in four different cases: the first was a case without load, the second was when water was used, then silicone oil, and finally, with silicone oil inserted in the erythritol-based TES. With 0.7 multi-fiber boards and 0.6 mm stainless steel side walls, the cooker was mounted on a wooden base with a rotatable zenith mechanism. The SC area was 0.681 $m^{2,}$ and the receiver glass area was 0.167 m^2, so the concentration ratio was 4.08. For the temperature range 125–100 °C, the average subject-cooling time was 351.16% longer than without the TES solution.

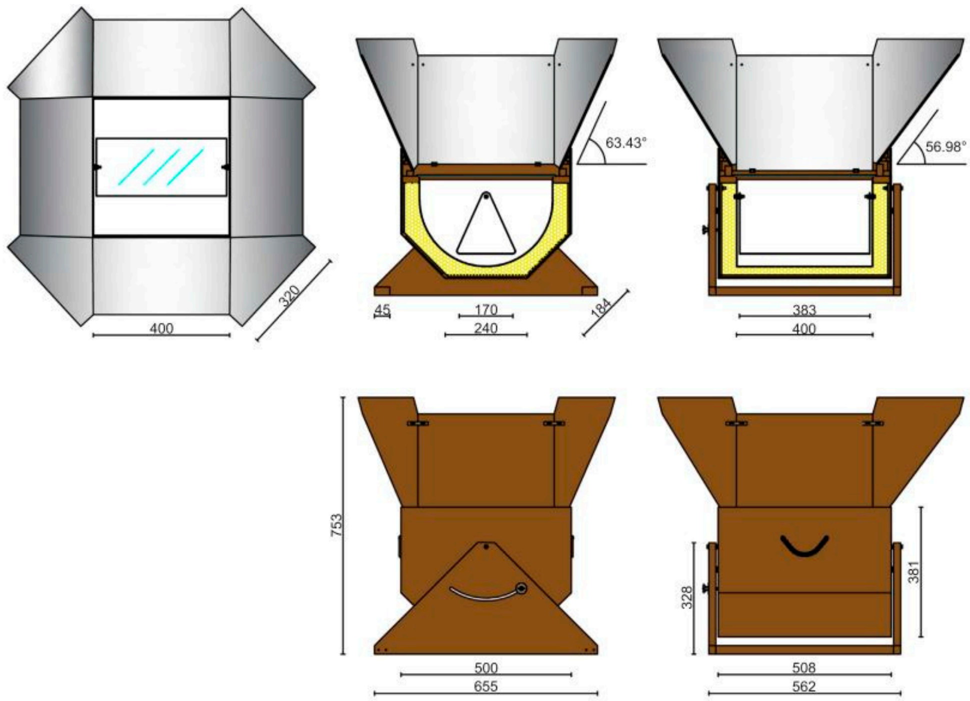

Figure 21. Cross-sectional view of the portable solar box cooker. Reprinted/adapted with permission from Ref. [64], 2020, Elsevier.

Bhandari et al. [65] used benzoic acid, paraffin wax, and magnesium nitrate hexahydrates in hybrid SC with PV technology, and in evening hours as an energy storage medium, benzoic acid has the best thermal performance. Regarding the case without PCM, the average thermal efficiency for a hybrid PV cooking system using PCM was approximately 60%, which comes out to be 7–10 times more. Further, the hybrid SC may be used for cooking even when the sun is not shining.

Mwaura and Thoruwa [66] used acetanilide with a double reflector SC with length to depth ratio of 4:1, and the test was conducted three times: first, without loading the cooking pot of the cooker, second, with water as the cooking load, and third, with different actual cooking loads in the experimental study. The two pots with and without PCM attained an average stagnation temperature of 85.9 ± 24.0 °C and 82.7 ± 24.3 °C, respectively. A coefficient of performance of 0.754 was attained in the cooking power testing. The findings revealed that the double reflector SC (Figure 22) with energy storage could prepare meals during the day and evening. Evening cooking was found unaffected by noon cooking.

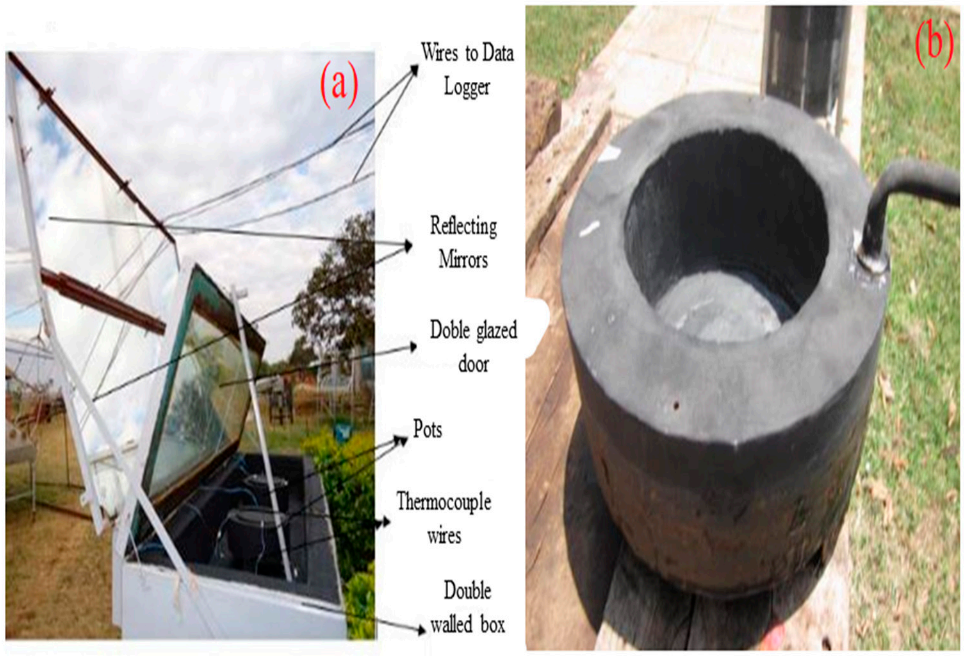

Figure 22. Solar cooker set with PCM storage unit: (**a**) Experimental setup; (**b**) PCM storage unit. Reprinted/adapted with permission from Ref. [66], 2019, Jomo Kenyatta University of Agriculture and Technology.

Milikias et al. [67] designed a better-quality box-type SC equipped with sensible heat storage. The designed SC was constructed so that it could use only 20% less inner surface area than another simple SC with a similar sunray capture area. The experiment was conducted under both stagnation and loaded condition. When compared with the conventional SC, the F_1 result with a conventional kind of setup was only 0.115, while it was 0.1349 with black stone as TES, 0.1238 with concrete, and 0.1453 without any TES with improved structure. The obtained value for F_1 with improved structure was in accordance with the Indian standard and was categorized as grade A because it was more significant than 0.12.

Unger et al. [68] thoroughly reviewed the insulated solar electric cooker use, the current usage of PCM in various industrial and household applications, and its relevant patents, various design concepts with various PCMs, their alternatives, and validation modeling. They specifically used erythritol in the insulated solar electrical cooker, where 1 l of water was boiled for 20 min using the solar electric cooker. The use of PCM-led SC retains heat for more than 4 h.

Yuksel et al. [55] designed a novel box-type SC incorporating paraffin wax with metal shavings as TES material suitable for both daylight and late-evening cooking. The diagram of this SC is shown in Figure 23. The experiment was conducted in June and July. The experiment was performed at different reflector angles to assess the thermal efficiencies under various conditions. The results revealed that 30° was a suitable reflector angle. The thermal efficiency was enhanced by 18.35% by the use of reflectors. The temperature of the paraffin reached between 75.1 °C and 80.5 °C. The heating time was also reduced by about 1 h. The effectiveness of the paraffin as PCM can be assessed in terms of the high temperature reached and reduced cooking time.

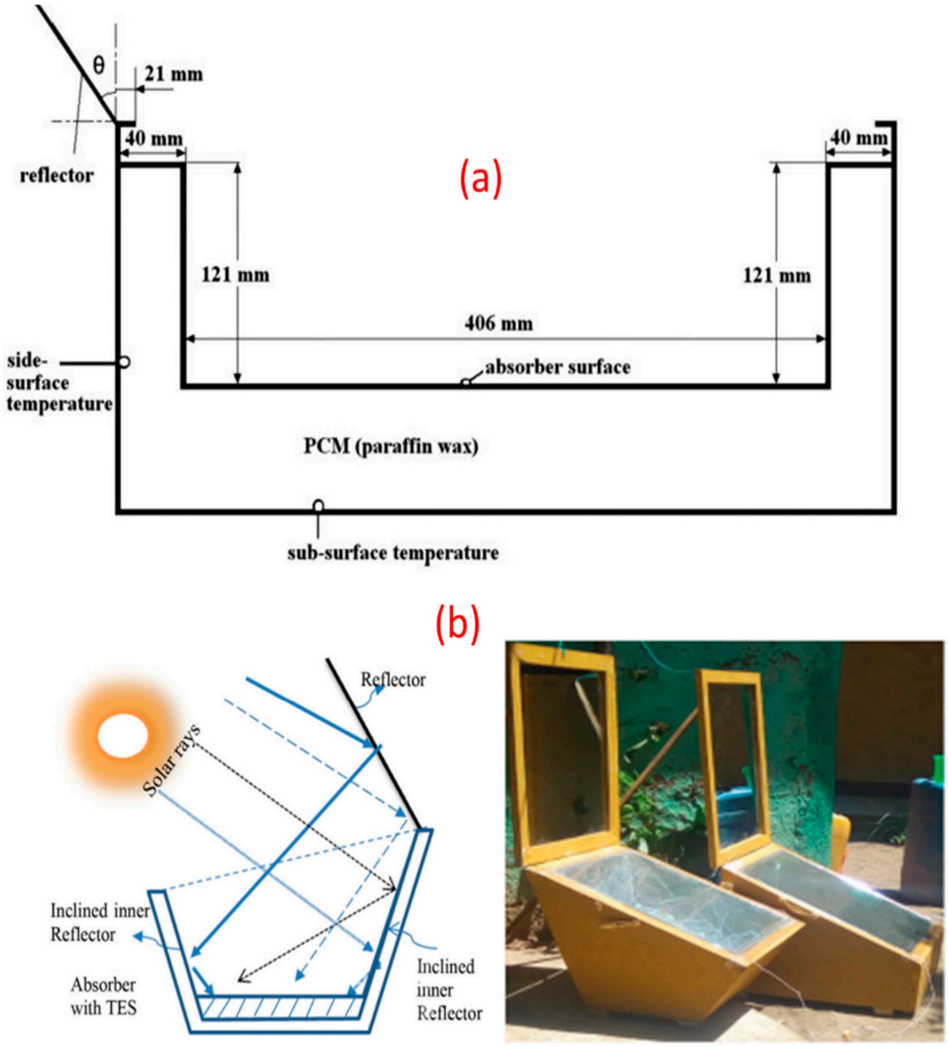

Figure 23. (**a**) Schematic diagram; (**b**) Experiment setup of box-type SC. Reprinted/adapted with permission from Ref. [55], 2012, AIP Publishing and Ref. [67]. 2021, Taylor & Francis online Publishing.

Various PCMs studied in different experiments have been compiled as a table and placed with proper reference, wherein properties have been mentioned against the PCMs presented in Table 2.

Table 2. Thermophysical properties of the PCMs.

Sl. No.	Phase Change Material (PCM)	Melting Temp (°C)	Latent Heat of Fusion (kJ/kg)	Specific Heat Capacity J/kg.k	Reference
1	Acetanilide	118.9	222	-	[46]
2	Stearic Acid	89	162.8	1.84	[50]
3	Magnesium Nitrate Hexahydrate	82	263	1.94	[51]
4	Acetamide	56–60	189	2.95	[53]
5	Paraffin Wax	67–69	202.5	2.8	[55]
6	Ternary mixture of nitrite and nitrate salts (solar salt: 53 wt% KNO_3, 40 wt% $NaNO_2$, 7 wt% $NaNO_3$)	145.14	101.5	1.4	[63]

Table 2. *Cont.*

Sl. No.	Phase Change Material (PCM)	Melting Temp (°C)	Latent Heat of Fusion (kJ/kg)	Specific Heat Capacity J/kg.k	Reference
7	Coconut Oil	22 to 26	114.6	2.1	[69]
8	Magnesium chloride hexa-hydrate ($MgCl_2$ $6H_2O$)	115–117	165–169	-	[70]
9	Capric Acid	30.1	150–158	-	
10	Lauric Acid	41–43	212	-	
11	Pentadecane Acid	52.5	159	-	
12	Palmitic Acid	59.9	198	-	
13	Myristic Acid	53.8	192	-	
14	Stearic Acid	55.1	160	-	
15	Erythritol	118	340	-	

Various studies and models have been made for the optimum selection of PCM for an SC along with energy and exergy [71] analysis. The multi-criteria decision-making model has been made with techniques such as TOPSIS, EDAS, and MOOR [72]. The result of one study has been mentioned here in Table 3, wherein the MOORA technique has been used, and erythritol has been found to be the first preference for PCM.

Table 3. Ranking of PCMs using the MOORA method with different criteria weights. Reprinted/adapted with permission from Ref. [72], 2021, Elsevier.

	AHP-MOORA		ENTROPY-MOORA		CRITIC-MOORA		COMPROMISED WEIGHS (Wj)—MOORA	
	NAV	Rank	NAV	Rank	NAV	Rank	NAV	Rank
Acetanilide	0.372	4	0.319	4	0.283	4	0.364	3
Erythritol	0.51	1	0.441	1	0.342	1	0.529	1
Paraffin wax	0.266	5	0.269	5	0.276	5	0.246	5
$MgCl.6H_2O$	0.392	3	0.329	3	0.285	3	0.352	4
Oxalic acid di-hydrate	0.509	2	0.381	2	0.299	2	0.521	2

The benefits associated with box-type SC are a simple design, flexibility in construction, and low monitoring requirement during the cooking period. Due to the strong and simple construction, the box-type SC is stable and has low maintenance costs. Further, this SC can also be easily transported from one place to another. Besides cooking food, it can also be used for keeping meals warm during off-sunshine hours. Simple box-type solar cookers do not pose risks of fire and burns, and no high glares are generally produced during operation. However, there are disadvantages: slow cooking rate due to low in situ temperature and intermittent sunshine may lead to partial cooking of food which may get wasted, as it cannot be kept for long. Even by adding reflectors and booster mirrors to the box-type SC, there is not much appreciation in the concentration ratio. Box-type SC has a concentration ratio of 10 with a low temperature of up to 100 °C.

9. Results and Findings

The performance parameter of various papers studied as part of work with many design modifications and with PCM has been tabulated in Table 4 below. The value of the parameters presented are as follows: the first figure of merit (F_1); the second figure of merit (F_2), stagnation temperature; standardized cooking power; energy efficiency; cost or affecting environmental parameter. Because all the parameters have not been provided in each study, only the mentioned parameters have been presented. Based on the analysis, the key findings have been mentioned as follows:

- It can be seen from the data presented that, in general, the solar cooker with a different type of design improvements has a value of F_1 near 0.12 m^2 °C/W and successfully meets the BIS standard for cooking food in the given conditions.
- The value of F_2 achieved in general for all the cases mentioned in Table 4 for 1 kg of water is from 0.33–0.47, which meets the BIS criteria.
- The stagnant temperature above 100 °C has been achieved for most cases, which shows that solar cooking can be achieved with the design proposed.
- The effect on the environment has been calculated by the amount of wood saved per year for the number of days when the cooking is done with a solar cooker.

Table 4. Performance Parameters; Energy efficiency; Cost of various solar cookers.

Sl No.	Year	Location	Author	First Figure of Merit (F_1)	Second Figure of Merit (F_2)	Stagnation Temperature	Standardized Cooking Power	Energy Efficiency	Cost	Environmental Effecting Parameter
1	2010	Algeria	Harmim et al. [16]	-	-	140 °C	-	-	-	-
2	2012	Algeria	Harmim et al. [33]	0.1681 m^2 °C/W	0.329 at 1 kg of water	140.5 °C	-	-	-	-
3	2012	India	Misra et al. [35]	0.1424 m^2 °C/W	0.4077 at 1 kg of water		-	-	-	-
4	2013	Algeria	Harmima et al. [34]	0.152 m^2 °C/W	0.47 at 3.5 kg of water without reflector	with reflector maximum absorber-plate temperature 166 °C	78.9 W	-	-	-
5	2013	Nigeria	Folaranmi et al. [36]	0.1135 m^2 °C/W	0.3172 for 2 kg of water	119 °C	-	-	-	-
6	2015	Spain	Soria et al. [37]	-	-		-			480 kg wood saved for 328 cooking days
7	2015	India	Mahavara et al. [38]	0.116 m^2 °C/W	0.466 at 1 kg of water	for bare plate without reflectors 144 °C	29.8 W		Rs 1385 per unit	-
8	2018	India	Saxena et al. [39]	0.12 m^2 °C/W	0.41 m^2 °C/W at 1.2 kg of water	-	60.20 W	thermal efficiency—45.11%	-	-
9	2020	Egypt	Khallaf et al. [42]	0.0657 m^2/W	0.085 to 0.76 for the mass of water from 0.5 kg to 4.0 kg	113.6 °C	-	-	-	-
10	2021	India	Vengadesan et al. [45]	-	-	102 °C for a fin with max height	-	56.03%	-	-
11	2021	Egypt	Tawfik et al. [25]	0.12 m^2 °C/W	-	100 °C	-	overall cooking efficiency 12.5%	reduce the LCOH and LCMM by ~44.1% and ~18%, respectively	-
12	2017	Tunisia	Guidara et al. [27]	0.14 m^2 °C/W	0.39	133.6 °C	-	-	-	-

10. Conclusions

This paper has reviewed the latest development and design improvements in the box-type SCs using various mechanical modifications, add-on reflectors, and transparent insulating materials in the experiments conducted over recent years. Various heat equations and the existing method of calculating costs, such as payback period (PP), net present value (NPV), benefit–cost (B–C) ratios, internal rate of return (IRR), levelized cost of heat (LCOH), levelized cost of cooking a meal (LCCM) along with energy efficiency, exergy, and environmental effect, have been explained with a case of sample solar cooker. Various PCMs have been studied, and a multi-criteria decision-making model for choosing and optimizing PCM has been elaborated. The results of various studies and their findings have also been briefed discreetly. It can be stated that with the help of the design improvements and latest developments mentioned in the paper, the comprehensive design for a solar cooker can be made and analyzed, and its performance can be simulated beforehand to meet the end use. It has been established vide research work that solar energy stored in a thermal energy storage system can be efficiently utilized for cooking during off-sunshine hours. Further incorporation of better government policies can bring social acceptance of this green and clean energy usage for its widespread percolation. The realization of SDG 7 and SGD 13 of the United Nations Mandate can be accomplished using solar energy most efficiently and cost-effectively.

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Nomenclature

A_{eff}	Effective aperture area of the solar cooker	A_{gu}	Aperture area of upper glass
$C_{a,m}$	Cost of yearly savings	A_{gl}	Aperture area of lower glass
C_{lpg}	Cost of LPG per kg	A_v	Aperture area of vessel
$C_{o,m}$	Operation and maintenance cost	A_{mr}	Aperture area of mirror
C_{sc}	Salvage value of the box-type solar cooker	A_{ab}	Area of absorber plate
$C_{i,sc}$	Capital cost	A_{vb}	Area of vessel base
d	Discount rate	α_{ab}	Absorptivity of solar radiation on absorber plate
F_{mr}	View factor which is taken unity in this case	α_v	Absorptivity of solar radiation on vessel/pot
E_t	Energy saved	α_{gu}	Absorptivity of solar radiation on upper glass
$h_{c.gu\text{-}am}$	Convective heat transfer coefficient of upper glass to ambient	α_{gl}	Absorptivity of solar radiation on lower glass
$h_{r.gu\text{-}sky}$	Radiative heat transfer coefficient glass upper to outside air	$h_{c.v\text{-}f}$	Convective heat transfer coefficient vessel to fluid
$h_{r.gl\text{-}gu}$	Radiative heat transfer coefficient glass lower to upper	$h_{r.vc\text{-}gl}$	Radiative heat transfer coefficient vessel to lower glass
Θ_o	Exergy output	$h_{c.vc\text{-}a}$	Convective heat transfer coefficient vessel to air in SC
H_{exp}	Average solar radiation exposed	$h_{c.a\text{-}gl}$	Convective heat transfer coefficient ambient to lower glass
H	Solar radiation	$h_{c.ab\text{-}a}$	Convective heat transfer coefficient ambient to air in SC
H_{Cpw}	Specific heat of water	$h_{c.ab\text{-}gl}$	Convective heat transfer coefficient ambient to lower glass

h	Heat transfer coefficient	$h_{c.gl\text{-}gu}$	Convective heat transfer coefficient lower to upper glass
I_d	Diffused solar radiation	$h_{r.ab\text{-}gl}$	Radiative heat transfer coefficient ambient to lower glass
I_s	Solar radiation	MC_p	Heat capacity of upper glass
I_G	Solar radiation on glass	$Q_{r,gl\text{-}gu}$	Radiative heat from lower to upper glass
I_b	Beam Solar radiation	$Q_{c,\ gl\text{-}gu}$	Convective heat from lower to upper glass
M_{lpg}	Mass of LPG consumed per month	$Q_{c,v\text{-}a}$	Heat convective vessel to air in solar cooker
Ml_t	Meals cooked per year	Q_{sw}	Heat from side wall
n	Number of vessels (01 in this sample case)	Q_v	Heat from vessel/pot
Q_f	Heat from fluid in vessel/Pot	$Q_{red\ CO2}$	Quantity of CO_2 reduced while using a box-type SC in place of a conventional LPG,
η	Optical efficiency	Q_{am}	Ambient heat
ϵ	Thermal exergy	Q_{gl}	Heat on glass lower surface
Q_{gu}	Heat on upper surface of glass	$Q_{total\ CO2}$	Total quantity of CO_2 produced (in kg/month) conventional LPG
P_r	Percentage of the time a solar cooker is used	Q_{ab}	Heat at absorber base
T_{sky}	Temperature outside SC	$Q_{c,gu\text{-}am}$	Convective heat from lower glass to ambient air
T_{ab}	Stagnation temperature of the absorber plate	$Q_{sw\text{-}am}$	Heat from side wall to ambient air
T_v	Temperature of vessel/pot	$Q_{ab\text{-}am}$	Heat from absorber to ambient air
T_{am}	Ambient temperature	$Q_{r,gu\text{-}sky}$	Radiative heat from lower glass to sky
T_{w1}	Lower level of water temperature	$Q_{c,\ gu\text{-}sky}$	Convective heat from lower glass to sky
T_{w2}	Upper level of water temperature	$(Q_c + Q_r)_{gl\text{-}gu}$	Heat convective and radiative from lower to upper glass
t	Time interval when the temperature of water rises from T_{w1} to T_{w2},	$Q_{c,\ ab\text{-}a}$	Convective heat from ambient to air
t_{exp}	Time interval of the experiment	Q_u	Heat from absorber plate to vessel
T_s	Surface temperature of the sun	$Q_{c,v\text{-}f}$	Convective heat from vessel to fluid
T_a	Temperature of air inside solar cooker	$Q_{c,\ a\text{-}gl}$	Convective heat from ambient to lower glass
T_f	Temperature of fluid	$Q_{r,v\text{-}gl}$	Radiative heat from vessel to lower glass
T_{gu}	Temperature of upper surface of glass	$Q_{r,ab\text{-}gl}$	Radiative heat from ambient to lower glass
T_{gl}	Temperature of lower surface of glass	Ψ	exergy efficiency
U_{Ls}	Heat loss factor	S	Solar flux
U_{vb}	Heat loss by vessel base	τ_{gl}	Transmissivity of lower glass
U_{sw}	Heat loss by side wall	τ_{gu}	Transmissivity of upper glass
U_{ab}	Heat loss by vessel base	Φ	Angle of incident from mirror to upper glass cover

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