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A review of solar, electric and hybrid cookstoves

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ABSTRACT

The research on clean and energy-efficient cooking technologies has focused on solar and electric cookstoves. Recent studies have proposed solar-biomass and solar-electric hybrid cookstoves towards developing renewable and sustainable cooking technologies. However, only solar cookstoves have been reviewed extensively, owing to the vast literature. This article reviews electric and solar-hybrid cookstoves for the first time and summarises the recent developments in solar cookstoves. Though solar cookstoves offer clean and cost-free operation, they depend on sunlight availability and usually have longer cooking durations due to low operating power. Direct solar cookstoves require cooking outdoors, whereas indirect cookstoves enable indoor cooking using a heat transfer fluid. Also, thermal energy storage facilitates night cooking. Electric cookstoves function based on induction, resistance or radiative heating principles. However, off-grid and rural areas lack a continuous supply of electricity. Hybrid cookstoves combine solar energy with fuels and electricity to achieve renewability. Total system efficiency, which includes the efficiencies of energy production, transportation and end-use, is a better indicator of the cooking life cycle. Electric cooking depicts low total system efficiency despite having the highest end-use efficiency (about 80%) due to low efficiency of electricity production and transportation. In contrast, the total system efficiency of solar cooking equals its end-use efficiency. Recent advancements in solar cookstoves have shown efficiencies up to 35–40% with direct and 63–69% with indirect solar cookstoves. The present review also identifies directions for future research. Specifically, the gaps in hybrid cookstove literature call for future research to develop sustainable cooking technologies.

1. Introduction

Cooking takes up a significant portion of the household energy requirement. Cookstoves produce the required heat using fuel combustion, electricity, or solar radiation. Combustion cookstoves fuelled by biomass, kerosene, LPG, and natural gas are prevalent worldwide. These cookstoves emit pollutants and greenhouse gases, elevating health hazards and global warming. Fig. 1 shows that only small proportions of the population in several countries rely on clean cooking devices. About 3 billion people depend on polluting fuels and inefficient cooking devices worldwide, exposing themselves to 100 times the acceptable limit of air pollution. Such indoor air pollution could lead to several diseases, such as pneumonia, lung cancer and chronic obstructive pulmonary disease, which has caused about 3.8 million premature deaths [1]. Furthermore, the greenhouse gases such as carbon dioxide and methane released from combustion cookstoves tend to escalate global warming. Thus, shifting to renewable cooking helps in transition to net zero emissions [2,3].

Though solar and electric cookstoves offer clean alternatives, the latter does not help mitigate global warming since about 62% of the electricity worldwide is produced from fossil fuels [5]. Solar cookstoves present attractive benefits such as pollution-free operation, zero emission of greenhouse gases, and they operate on renewable solar energy. Therefore, several researchers have paid attention towards improving the solar cookstove performance. Khatri et al. [6] reviewed the recent developments in solar cookstove technology and summarised the socio-economic and policy aspects that affect the dissemination of solar cookstoves. Cuce and Cuce [7] presented an extensive review of solar cookers classified under three broad categories – panel type, box type and parabolic cookers. Analysis of cooker performance, evaluation of thermodynamics, novel concepts to improve cooker efficiency and environmental aspects have been discussed. Herez et al. [8] included an energy/exergy analysis, presented an economic study to estimate the payback period, and presented an environmental study to quantify the reduction in carbon dioxide emissions. Omara et al. [9] have discussed in detail the developments in solar cookstove designs with integrated phase change material (PCM) for thermal energy storage, focusing on

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List of abbreviations:

AC	Alternating Current
CPC	Compound Parabolic Concentrator
FEM	Finite Element Method
HTF	Heat Transfer Fluid
IAO	Antimony-doped Indium Oxide
ISSBH	Improved Small Scale Box-type Hybrid
LPG	Liquified Petroleum Gas
MCDA	Multi-Criteria Decision Analysis
MPPT	Maximum Power Point Tracking
MWCNT	Multi-Walled Carbon Nano Tube
PCM	Phase Change Material
PEM	Proton Exchange Membrane
PID	Proportional-Integral-Derivative
PV	Photo-Voltaic
SFSC	Single Family Solar Cooker
SLS	Soda Lime Silicate
TES	Thermal Energy Storage

the latent heat storage method. The benefits of PCMs in improving cooking performance, achieving evening cooking, and shortening cooking time have been elaborated. Lahkar and Samdarshi [10] have reviewed the thermal performance parameters of box-type cookstoves reported in the literature. They also suggested objective parameters that convey all the required information to choose a suitable solar cookstove for a given geography and climate. Several other review articles have focused on solar cookstoves [11–15].

Hybrid cookstoves that utilise multiple sources of energy have also been proposed in the literature, for instance, solar-biomass and solar-electric hybrid cookstoves. However, a review of electric and hybrid cookstoves has not been carried out previously, to the best knowledge of the authors. The present study intends to fill the void by reviewing the technical aspects of solar, electric and hybrid cookstoves. The following sections classify the cookstoves (Section 2) and present their testing parameters (Section 3), followed by a detailed review of the cookstove literature (Section 4), a comparison of these cookstoves and suggestions for future research (Section 5).

2. Cookstove classification

Based on the energy source used to heat the cooking vessel, we classify domestic cookstoves as combustion, solar, electric and hybrid cookstoves (Fig. 2). Combustion cookstoves can be further classified as gaseous, liquid or solid fuel and a porous radiant burner that can combust gaseous and liquid fuels. Under solar cookstoves, direct stoves provide heating by focusing the sunlight on the vessel. In contrast, indirect stoves transfer solar energy to the cooking vessel placed indoors using a heat transfer fluid. Electric cookstoves consist of induction, resistance and radiative types of heating. Hybrid cookstoves are novel developments that utilise multiple sources of energy to heat the vessel. These include hybrids of solar energy with fuel combustion and electricity.

3. Cookstove performance testing

Solar cookstoves are often tested by heating water. Parameters such

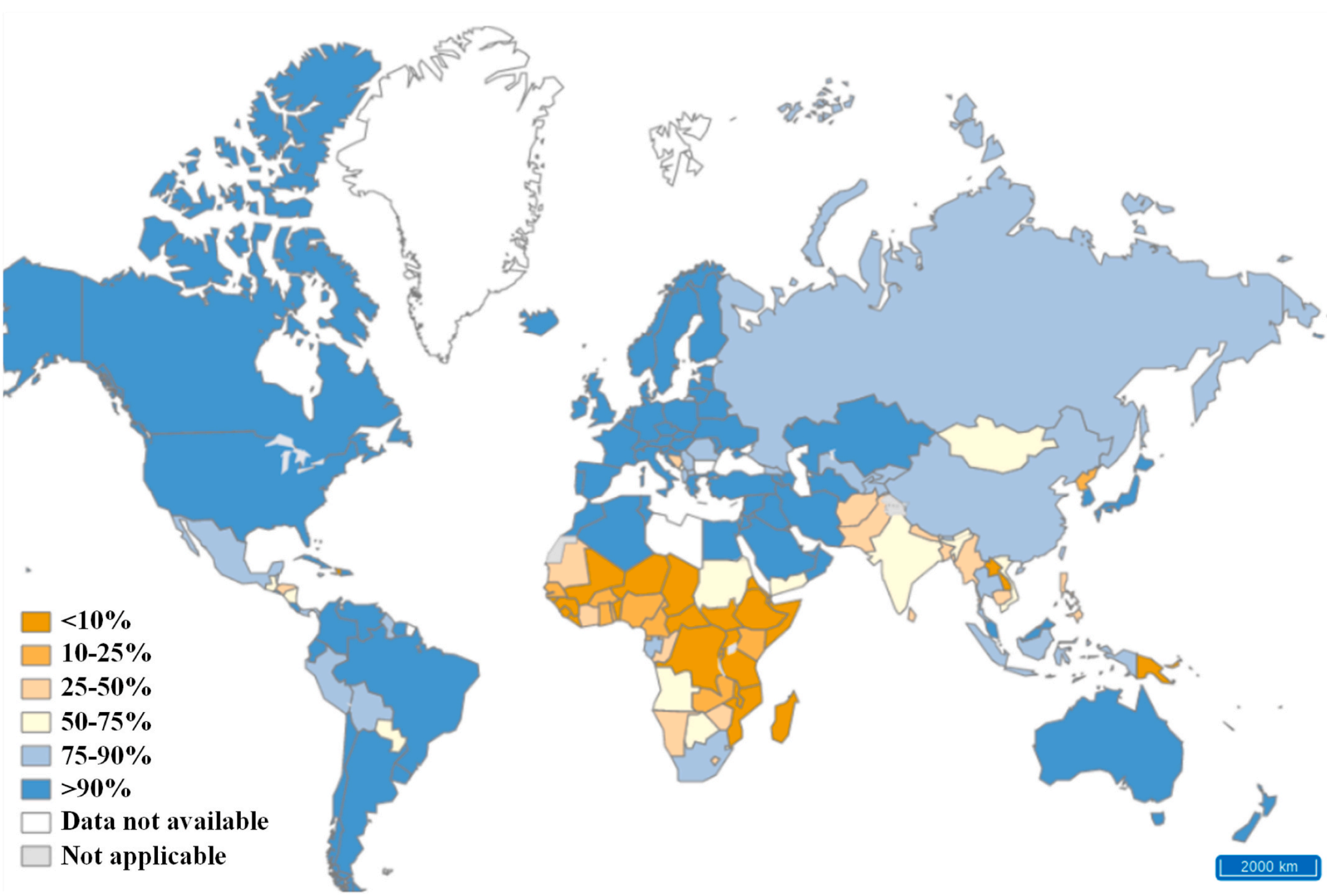

Fig. 1. Map depicting the proportion of the population that depends on clean fuels and devices for cooking [4].

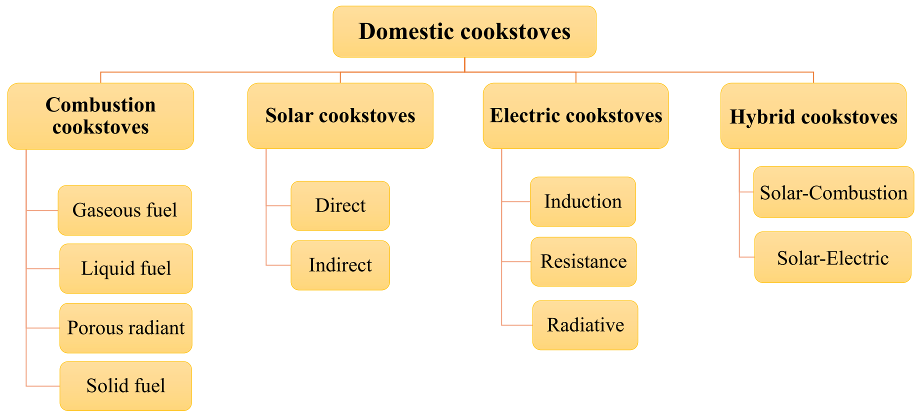

Fig. 2. Classification of domestic cookstoves.

as energy and exergy efficiencies and two figures of merit have been used to evaluate the cookstove performance. These parameters are defined and discussed briefly in Table 1. The literature on electric cookstoves mostly reports energy efficiency.

4. Review of cookstoves

The following sub-sections present a detailed review of solar, electric and hybrid cookstoves. First, we discuss the fundamental physics governing the cookstove operation and the effects of various parameters on the cookstove performance, followed by a discussion of advancements in cookstove technologies.

4.1. Solar cookstoves

Solar cookstoves focus the sunlight on a small region to heat the cooking vessel directly in case of direct cookstoves. However, indirect cookstoves first heat a fluid referred to as a heat transfer fluid that heats the cooking vessel placed indoors. Thermal storage can be used along with both stove types to enable cooking during hours of no sunlight. Solar cooking has been reviewed by many researchers [6–15]. Hence, this article highlights only the recent research developments.

In indirect cookstoves, heat transfer fluids must possess high boiling and low melting points, considering the operating temperatures. Low viscosity and high thermal conductivity facilitate faster heat transfer to the cookstove [19]. To enable night-time cooking, thermal storage methods such as sensible or latent heat storage could be adopted. The quantity of sensible heat stored depends on the specific heat and mass, whereas the amount of latent heat stored depends on the mass and latent heat of phase change. Latent heat storage offers a higher density of energy storage and a wider range of operating temperatures compared to sensible heat storage. However, sensible heat storage has a longer life than latent heat storage. Higher specific heat, latent heat and storage density lead to higher energy storage and a higher thermal conductivity results in faster energy storage and release. The thermal conductivity and specific heat of PCMs could be enhanced using novel techniques, such as the addition of nanomaterials and encapsulation [20].

4.1.1. Direct solar cookstoves

4.1.1.1. Box type cookstoves. Typical box-type solar cookstoves consist of an insulated box with a transparent window made of glass. A reflector focuses the sunlight towards the vessel. The cooking vessel and the cookstove walls absorb solar radiation. The window is transparent to incoming solar radiation but reflective to the radiation leaving the box, thus trapping heat inside the cookstove [8].

A Single Family Solar Cooker (SFSC), theoretically designed and tested by Mahavar et al. [21], had a small size, lightweight insulation and lightweight polymeric glaze (Fig. 3a). A maximum plate stagnation temperature of 144 °C was observed under the no-load condition. The SFSC performed well in cooking two meals for two persons. Amer [22] developed a double-exposure solar cookstove that focused sunlight from both above and below the cooking vessel. Two diffuse reflectors were placed below the cookstove to focus sunlight on the bottom of the absorber. Steady and transient tests with no-load revealed that absorber temperatures as high as 165 °C could be achieved. The cookstove also showed 30–60 min faster cooking times than the conventional cookstove. Mirdha and Dhariwal [23] observed higher plate temperatures by including additional booster mirrors that could be adjusted in three positions. The temperature was sufficient to cook two meals a day and keep the food warm during late evenings. The improved design was suitable for use in a south-facing kitchen window and to operate from the rear opening. In the study of Ukey and Katekar [24], an octagonal box cookstove with a copper bottom plate provided a 26.55% increase in efficiency and 23.52% more cooking power compared to box type cookstoves in the market. The copper bottom plate maintained a constant temperature.

Harmim et al. [26] proposed a novel building-integrated design that could be easily fixed to a southern kitchen wall (Fig. 3c). This design included two fixed compound parabolic concentrators (CPC) and a step-shaped absorber plate. Under the no-load condition, the absorber plate temperature reached a maximum of 166 °C with the CPC reflector and 127.7 °C without the CPC reflector. The user-friendly design allows easy supervision during cooking and avoids frequent outdoor visits. Two meals could be cooked effectively per day for a family of four people. Fig. 4a shows the variation of temperature and solar radiation with a load.

Covering the cooking pot with a glass lid increases thermal efficiency, as observed by Sagade et al. [29]. Glass lid allows solar radiation to enter the cooking pot. At the same time, it absorbs all the radiation emitted by the pot interior, reducing heat losses. The disadvantage of glass cracking could be overcome with toughened or tempered glass. The heating and open sun cooling tests confirmed the favourable effect of the glass lid. Ghosh et al. [30] recommended a glass pane coated with low-emissivity Antimony doped Indium Oxide (low-e IAO) film. The low-e film provided a lightweight alternative to uncoated soda lime silicate (SLS) glass. An evacuated double-glazed glass provides much better thermal insulation than the low-e glass. But low-e glass has a lower weight, low cost, lower risk of thermal shock and rupture, and is easy to fabricate and use, making it preferable.

An absorber plate with fins (Fig. 3d) has shown a 7% higher stagnation temperature than the unfinned plate in the study of Harmim et al. [27]. The time for boiling water was also 12% lower. Fins improve performance because multiple reflections of solar radiation increase the absorber temperature, and the absorber, in turn, exchanges heat with the internal air through the fins. In another study by Cuce and Cuce [31],

Table 1
Solar cookstove testing standards and their formulae for efficiency calculation (*Notation:* m_w- mass of water in the vessel (kg), C_w - specific heat of water [kJ/(kg K)], T_1 - initial temperature of water (°C), T_2 - final temperature of water (°C), ΔT - temperature rise of water (°C), V_{fuel} - volume of fuel consumed (m^3), M_{fuel} - mass of fuel consumed (kg), T_a - ambient temperature (K)).

Standard	Efficiency formula (η in %)	Brief description
Indian Standard IS 13429:2000 [16]	Recommends evaluating the solar cookstove using first and second figures of merit as defined below.	
First figure of merit (F_1) [17]	$F_1 = \frac{\eta_o}{U_L} = \frac{T_{p,s} - T_{a,s}}{IG}$ $T_{p,s}$ - stagnation temperature of the absorber plate (K) $T_{a,s}$ - temperature of the ambient air at stagnation (K) IG - insolation on a horizontal surface at stagnation (W/m^2) η_o - optical efficiency U_L - heat loss factor (W/m^2-K)	• F_1 concerns stagnation or max—temperature of the absorber plate under no-load conditions. • It is the ratio of optical efficiency and the heat loss factor • F_1 has units m^2K/W
Second figure of merit (F_2) [17]	$F_2 = \frac{F_1\, m_w C_w}{A_c \Delta t}\, ln\left[\frac{1 - \left(\frac{1}{F_1}\right)\frac{(T_1 - \overline{T_a})}{\overline{IG}}}{1 - \left(\frac{1}{F_1}\right)\frac{(T_2 - \overline{T_a})}{\overline{IG}}}\right]$ A_c- cover area or aperture area (m^2) Δt - time taken for heating water from T_1 *to* T_2 (in s) $\overline{T_a}$ - average ambient temperature (K) $\overline{IG}$ - average insolation during Δt (W/m^2)	• F_2 relates to the stove performance while heating the load (water)
Energy efficiency [18]	$\eta = \frac{m_w\, C_w (T_2 - T_1)}{IG \Delta t\, A_{sc}}$	• Energy efficiency is defined as the increase in energy of water to the input solar energy
Exergy efficiency [18]	$\eta_{ex} = \frac{m_w\, C_w\left[(T_2 - T_1) - T_{r,a}\ln\left(\frac{T_2}{T_1}\right)\right]}{IG\Delta t\, A_{sc}\left[1 - \frac{4T_a}{3T_s}\right]}$ All temperatures in K A_{sc} - intercept area of the solar cooker (m^2) IG - total instantaneous solar radiation $T_{r,a}$ - reference ambient temperature (K) T_a - ambient temperature (K) T_s - surface temperature of the sun (K)	• Exergy efficiency is the ratio of the cooker's output exergy to the input exergy from solar radiation

a mathematical model was used to compute the temperature of a box stove with a finned absorber plate. Absorber plates with microporous surface configurations (Fig. 3b) depicted better thermal performance in the study of Cuce [25]. Trapezoidal porosity configuration resulted in the best improvement compared to semi-circular and triangular configurations. Since the trapezoidal structure features the largest linear length, it absorbs more solar radiation. As each trapezoidal section consists of three edges, reflected radiation gets recaptured. The energy and exergy efficiencies of the cookstove with ordinary absorber were 27.7–17.0 and 17.9–11.5%, while those with trapezoidal porosity absorber were 34.6–21.2 and 22.6–14.6%, respectively.

Sensible storage of energy using Bayburt stone in the cookstove has been studied by Cuce [28]. The Bayburt cookstove offered continuous and steady cooking till late evening by virtue of the thermal storage. In contrast, the conventional cookstove exhibited a drop in absorber plate temperature towards sunset (Fig. 4b). Owing to the higher specific heat of the Bayburt stone, the cookstove took longer to get heated compared to the conventional design. Energy and exergy efficiencies of the Bayburt cookstove (21.7–35.3%, 14.1–21.2%) were higher than conventional cookstoves (16.9–27.6%, 11.6–18%).

Latent heat storage using PCM (Phase Change Material) has been incorporated by Coccia et al. [32] in a modified cooking pot for use with a box stove. The PCM (erythritol) was filled in the annular region between two concentric pots bolted together. Eight booster mirrors intensified the sunlight reflected onto the cooking chamber. A maximum absorber temperature of 189 °C was observed with the no-load test. Heating of silicone oil as the load took longer with PCM because the additional mass of PCM consumes latent heat. However, the cooling time of silicone oil was longer by about 351.16% with PCM compared to without PCM. Thus, the thermal storage renders the cookstove useable even during no or intermittent sunlight.

A one-dimensional sun-tracking mechanism has been incorporated into a box-type cookstove by Farooqui [33]. The mechanism does not require a power source because it functions using the potential energy stored in a spring fixed to a water container. Sun tracking was more accurate when adjusted for a 3-h operation.

4.1.1.2. Concentrating type cookstoves. Concentrating solar cookstoves employ a parabolic reflector to focus all the incident sunlight at the vessel bottom (Fig. 5). Considering the principle of optics, the focal point of the concentrator is chosen for placing the cooking vessel. A tracking mechanism is required to ensure that the concentrator always faces the sun. A sun-tracking mechanism moves the concentrator to minimise the angle of incidence of the solar rays throughout the day. The mechanism tracks the sun's location both along north-south (seasonal tracking) and east-west directions (diurnal tracking) [13]. Al-Soud et al. [34] and Abu-Malouh et al. [35] have incorporated automatic sun-tracking systems with concentrating collectors. Fresnel lens collector has also been coupled with a tracking mechanism in the works of Valmiki et al. [36] and Farooqui [37]. Concentrating type cookstoves have a high concentration ratio (up to 50) and can achieve high temperatures (about 200 °C) in short intervals. Hence, constant supervision of the user is necessary to avoid burning the food [7,8,13].

Onokwai et al. [40] designed and fabricated a parabolic cookstove utilising locally available materials in Nigeria. The design included a parabolic dish and a wooden absorber box. The no-load test resulted in a maximum temperature of 121.7 °C, whereas during the sensible test (with load), a temperature of 100 °C was observed between 12:30 and 13:30 h. Ahmed et al. [41] found that Mylar tape reflector material concentrates higher solar energy in a shorter time compared to stainless steel and aluminium foil. Mylar tape reflective material is both cost-effective and energy-efficient. Further, a concentration ratio greater than 20 and an aluminium vessel with black coating were favourable. Goswami et al. [42] observed faster heating with charcoal (activated carbon) coated aluminium vessels. The highest temperature was attained in 60 min compared to 195 min with the uncoated vessel. Also, 1.59% higher efficiency compared to the regular vessel was observed. Hosseinzadeh et al. [43] developed a solar cooker to boil water filled in a stainless-steel cylindrical tank enclosed by two concentric glass tubes. The outer annulus was evacuated, and the inner annulus was filled with air. The outer tube was transparent, while the inner tube was coated with a selective multilayer absorber. Increasing the pressure of the vacuum envelope elevates the heat loss from the inner tube by convection, leading to a lower temperature and solar cooker efficiency. Higher coating absorptivity gives higher cookstove efficiency and useful

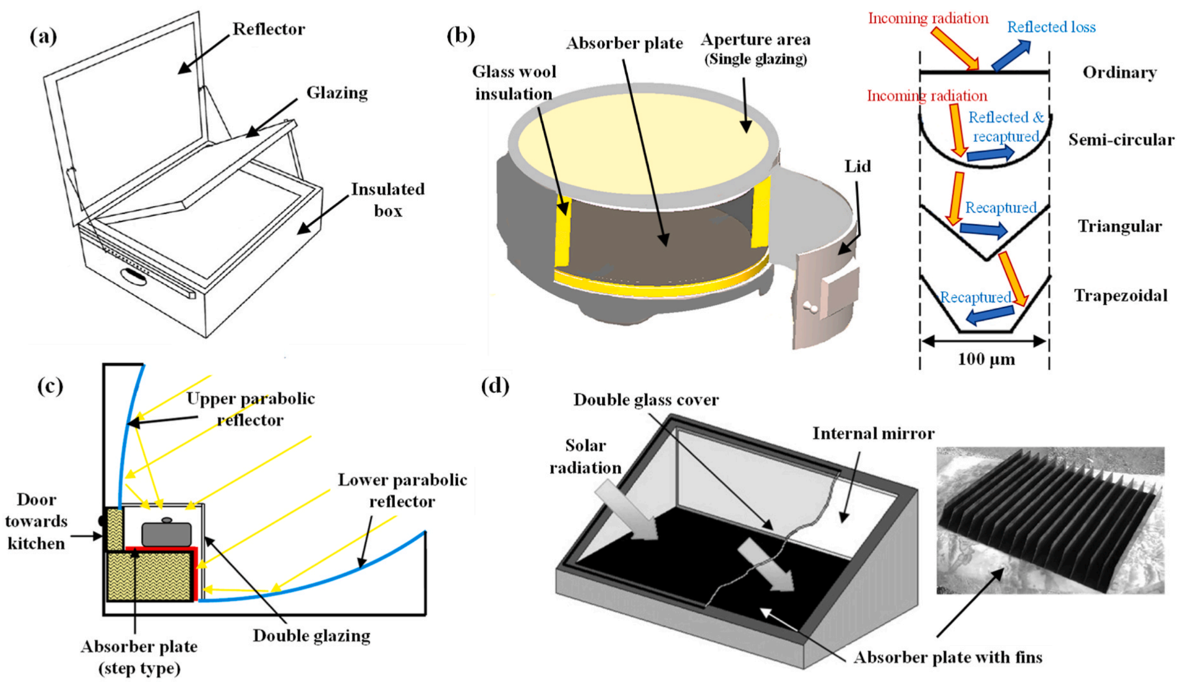

Fig. 3. (a) Schematic of Single-Family Solar Cooker (reprinted from Ref. [21] with permission from Elsevier), (b) Cylindrical box type cookstove and microporous absorber configurations (reprinted from Ref. [25] with permission from Elsevier), (c) Schematic of a building integrated box type solar cookstove (reprinted from Ref. [26] with permission from Elsevier) and (d) Box type solar cookstove and finned absorber plate (reprinted from Ref. [27] with permission from Elsevier).

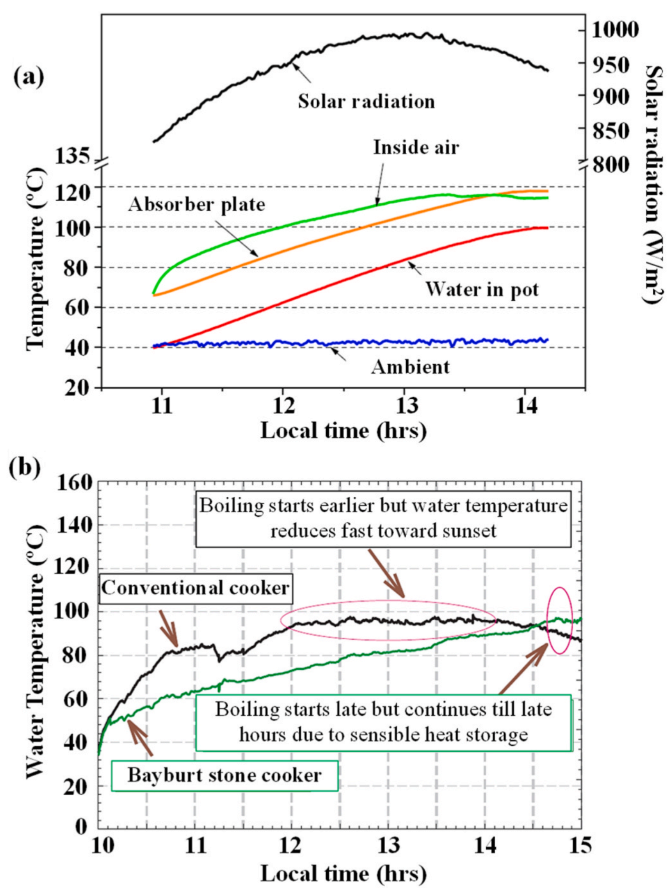

Fig. 4. (a) Temperature variation during water heating test in a building-integrated solar box stove (reprinted from Ref. [26] with permission from Elsevier), (b) Water temperature in a Bayburt stone integrated box type cookstove (reprinted from Ref. [28] with permission from Elsevier).

power.

Chaudhary et al. [44] studied the effect of latent heat storage using PCM (Acetanilide) in the cooking vessel. Acetanilide PCM was filled in the annular region between two walls of the cooking vessel. The vessel was placed on the absorber plate of the parabolic collector from 9 a.m. to 4 p.m. and later placed in a wooden insulator box. When filled in a black-painted vessel with a glazing enclosure, the PCM reached 186.3 °C by storing 32.3% more energy compared to 119 °C of the uncoated vessel without enclosure.

A solar frying pan for cooking injera bread has been presented by Gallagher [45]. The pan bottom, coated with a low-emissivity black absorber, heats up by solar radiation focused from a mirror placed below. The mirror was made of flat hexagonal panels of aluminised mylar. The fabricated prototype ensured the cooking of 4 kg of bread per hour, and the pan could reach 180 °C in a short time interval of 15–20 min. A novel artificial intelligence-based model has been proposed by Nazari et al. [46] to predict the plate temperature in a solar bread cooker with a concentrator. Adding a galvanised protector and an insulator cap minimised the heat losses. The cooking plate temperature reached 200 °C, and 10–12 soft pieces of bread could be cooked per hour for a minimum of 6 h on a sunny day.

4.1.2. *Indirect solar cookstoves*

Indirect cookstoves transfer solar energy to the cooking vessel placed indoors through a heat transfer fluid. A PCM (phase change material) can be used for energy storage. These cookstoves have been reviewed based on the type of collector used.

4.1.2.1. Flat plate and evacuated tube collectors. A schematic of a flat plate collector-type cookstove is shown in Fig. 6a. Hussein et al. [47] proposed an indirect cookstove consisting of a flat plate collector, indoor cooking unit and magnesium nitrate hexahydrate PCM indoor thermal storage. A copper absorber plate was welded with copper heat pipes (elliptical cross-section) and filled with distilled water. The water absorbs heat, vaporises and then condenses by transferring heat to the PCM and the cooking pot. The absorber plate received 24% more solar

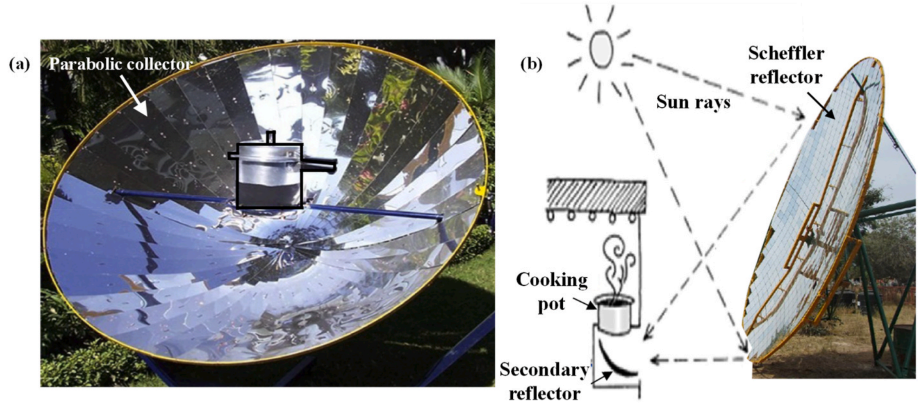

Fig. 5. Concentrating type direct cookstoves - (a) Solar cooker with a parabolic collector and (b) Scheffler dish cooker (reprinted from Refs. [38,39] with permission from Elsevier).

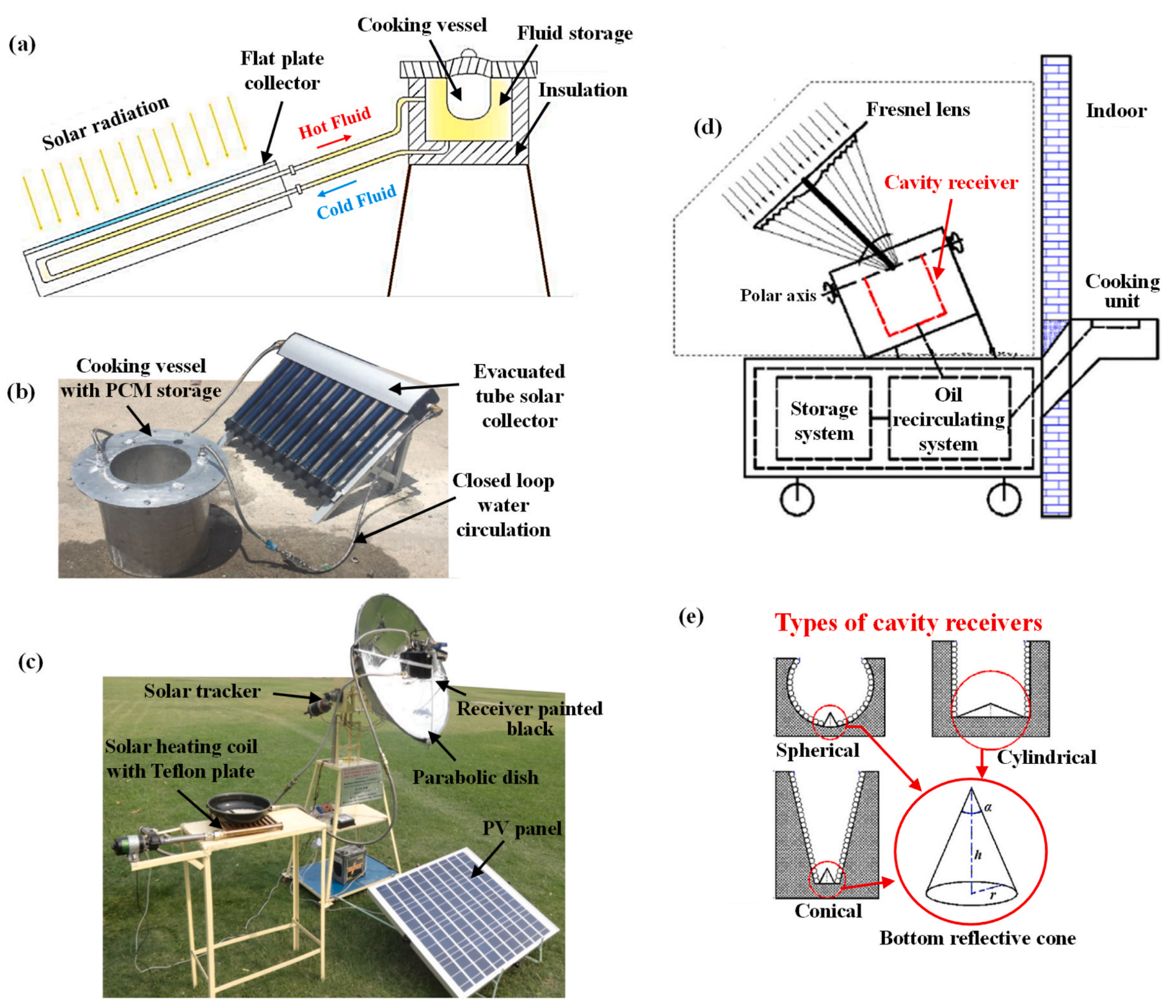

Fig. 6. Indirect solar cookstoves: (a) with a flat plate collector and indoor cooking unit – a schematic (reprinted from Ref. [8] with permission from Elsevier); (b) with an evacuated tube collector and cooking vessel with PCM storage (reprinted from Ref. [48] with permission); (c) with parabolic dish collector with a solar tracker, a receiver and a copper heater plate (reprinted from Ref. [49] with permission from Elsevier); (d) with a Fresnel lens concentrator and a cavity receiver; (e) shows different types of cavity receivers and the bottom reflective cone (reprinted from Ref. [50] with permission from Elsevier).

radiation when reflectors were included. This system could cook food in the noon and evening and maintain warmth during the night and early morning.

Esen [51] developed an indirect solar cookstove using a vacuum tube collector wherein a copper heat pipe was surrounded by two concentric glass tubes that maintained a vacuum around the heat pipe. Refrigerant (Freon 22, 134a or 407C) filled inside the heat pipes vaporised and rejected heat to Mobiltherm 605 oil in the condenser section, which heated the cooking pot. The cooking pot filled with 7 L of edible oil (cooking load) reached a maximum temperature of 175 °C. The cooking time varied with the refrigerant properties and meteorological conditions. An evacuated tube collector with water circulation has been incorporated by Nayak et al. [48], along with a cooking vessel having PCM storage (Fig. 6b). Acetanilide PCM was filled in the annular region between two concentric cylinders. Heated circulating water transferred energy to the PCM through a spiral heat exchanger immersed in the annular region. The cookstove could provide heating till 7:30 p.m., with a maximum PCM temperature above 120 °C and overall efficiency of 30%. By changing the heat transfer fluid from water to thermal oil, Singh et al. [52] found 18.88% higher energy imparted to the acetanilide PCM. Heat discharge from the PCM was slower with closed gate valves than with open valves. Thus, using thermal oil heat transfer fluid and keeping the gate valves closed during heat discharge provided an optimum operating condition to enable cooking in the daytime and at night-time in the Indian climate.

In a single vacuum tube solar cookstove, Farooqui [37] reported that an optimum cooking load of 6 kg water results in a maximum energy efficiency of 20–25%, exergy efficiency of 2.3–3.8%, and temperature of 250 °C. The solar radiation was focused on the vacuum tube using a primary reflector (Fresnel collector bed containing laser-aligned plane mirror strips). A secondary reflector focused sunlight from the primary reflector that missed hitting the vacuum tube. Thermal or vegetable oil served as the heat transfer fluid and circulated in the vacuum tube and the cooking chamber by natural thermal siphon action.

4.1.2.2. Concentrating collector. Nanofluids and thermal oil have been used as heat transfer fluids in a concentrating indirect solar cookstove studied by Hosseinzadeh et al. [53]. The cookstove included a parabolic concentrator, a receiver, heat transfer fluid and an indoor cooking unit (no thermal storage). MWCNT-oil (Multi-Walled Carbon Nano Tube-oil) nanofluid depicted a better overall efficiency. Increasing the mass fraction of nanoparticles in thermal oil resulted in higher overall efficiencies. The energy efficiencies with thermal oil and nanofluids containing 0.2% and 0.5% nanoparticles by weight were 12.85%, 15.93% and 20.08%, respectively. Also, 0.5 wt% MWNCT-oil nanofluid reduced the boiling time by 23 min (31.51%) compared to thermal oil. The improved heat transfer characteristics of the nanofluid are due to the dispersion of nanoparticles. Further, Hosseinzadeh et al. [54] found that SiC-oil nanofluid performed better than SiO_2-oil, TiO_2-oil and thermal oil. These nanofluids contained 0.5 wt% of SiO_2, TiO_2 and SiC nanoparticles in the thermal oil. Compared to thermal oil, SiC-oil could heat the load (water) 17 min (23.29%) faster and depicted 4.27% and 0.61% higher energy and exergy efficiencies, respectively.

In a concentrating type cookstove with a tracking mechanism, Singh [49] utilised Therminol 55 synthetic oil as the heat transfer fluid. A pump powered by a PV panel circulated the heat transfer fluid through a copper heater plate to heat the cooking vessel (a Teflon plate). The PV panel also drove the motors in the solar tracking mechanism (Fig. 6c). Maximum temperature of 109 °C, energy efficiency of 21% and exergy efficiency of 1.96% have been reported. The cookstove could successfully cook rice, potato, dal (pulses) and noodles. Wang et al. [50] utilised a fixed-focus Fresnel lens solar concentrator and a cavity receiver with a reflective cone in the bottom (Fig. 6d). Optical efficiency is the ratio of solar radiation absorbed by the cavity receiver to the total solar radiation incident on the Fresnel lens. To improve the optical efficiency of the receiver, an optimum reflective cone angle of 90° (Fig. 6e), a higher surface absorptivity of the receiver and a higher reflectivity of the cone are favourable. However, a lower surface absorptivity provides uniform heat flux since it allows for multiple reflections of sunlight. A Fresnel lens concentrator costs lesser than a Scheffler reflector since the latter has complex construction and installation. Also, manual sun-tracking increases labour costs [50].

4.1.3. Comparison of solar cookstoves

Parabolic and box-type cookstoves gave 44.2% and 39.5% energy efficiency when heating 1 L of water in the study by Onokwai et al. [40]. Improper placement of the cooking pot and thermal losses to the wind could deteriorate parabolic cookstove efficiency, as noted by Panwar et al. [55]. They observed higher energy and exergy efficiencies with box-type cookstoves. Based on a techno-economic evaluation of institutional cooking, Indora and Kandpal [38] found that a parabolic concentrating cookstove suitable to cook food for 25–30 persons could contribute 36–60% of the meals per year, while Scheffler dish type cookstove could achieve 59–85% of the annual meals. Though the parabolic type cookstove was cost-effective, its performance degrades if wind speeds are higher. However, the better-performing Scheffler cookstove requires higher capital investment. Ozturk [18] observed higher energy and exergy output with a parabolic-type solar cookstove than with a box-type cookstove. Exergy is a better tool to analyse solar cookstove performance because it accounts for the quality of energy. Pandey et al. [56] noted that a paraboloid cookstove was more exergy efficient than a box-type cookstove in all their experiments. While using thermal storage, boiling 1 L of water on the surface of a PCM storage in an indirect parabolic cookstove required 25% more time than a direct-type parabolic cookstove, as noted by Mussard et al. [57]. Simulations suggested that optimising the heat transfer surface of the thermal storage could render the indirect stove on par with standard solar cookstoves. The review work of Aramesh et al. [58] tabulates the overall efficiency of a wide variety of solar cookstoves in the literature. Direct parabolic cookstoves exhibit the maximum efficiency (53.45%–77%), followed by box cookstoves (10.69%–55.6%), and efficiency is the lowest with indirect parabolic trough cookstoves (15.7%).

Solar cookstoves are often adopted as an alternate cooking option along with LPG. The payback periods could be reduced if solar cookstoves are utilised for a larger fraction of the total cooking time besides LPG. The payback period is the time required to recover the investment cost of the solar cookstove. It was computed as the solar cookstove cost divided by the monthly money savings by replacing LPG with solar cooking [8].

4.1.4. Summary of solar cookstoves

Direct solar cookstoves enable heating by focusing sunlight on the absorber plate that heats the vessel. The performance of box cookstoves has been improved by reflecting more sunlight using booster mirrors or a concentrating parabolic concentrator (CPC) that resulted in an absorber plate temperature of 166 °C against 127.7 °C without CPC [26]. An absorber plate with fins or a microporous surface also improves the cookstove performance [25,27]. Though concentrating cookstoves (parabolic and Scheffler reflector type) achieve high temperatures in short durations due to the higher concentration ratio, they require sun tracking for continuous heating [13]. Indirect cookstoves enable indoor cooking through a heat transfer fluid. In the flat plate and evacuated tube collectors, the heat transfer fluid is filled in tubes, whereas in concentrating cookstoves, the heat transfer fluid is filled in a receiver. The use of nanofluid as the heat transfer fluid improves the cookstove performance [52]. Thermal storage using sensible heat or latent heat enables cooking during hours of no sunlight [28,32,47,48,52]. Solar cooking offers attractive features of cost-free operation and zero emissions. Though indirect cookstoves enable night cooking, they tend to increase initial costs. Long cooking times make solar cookstoves less preferred over other types. Table A. 1 summarises the studies on solar cookstoves.

4.2. Electric cookstoves

Electric cookstoves convert electricity into heat by inductive, resistive or radiative action. Each of these modes is reviewed in the following sub-sections.

4.2.1. Inductive cooking

An inductive heating system includes an induction coil and a conducting ferrous material that gets heated, referred to as a heat-piece. When applied to an induction coil, AC produces a time-varying magnetic field around itself. The electromagnetic field generates eddy currents in the heat-piece, resulting in Joule heating. In an induction cookstove (Fig. 7), the vessel acts as the heat-piece, gets heated up and conducts heat to the food inside. Induction heating requires the vessel to be ferrous and conducting. For the heating of non-ferrous vessels, ferrous material is used in the interface between the coil and the vessel [59].

The performance of induction heating depends on several factors: intensity and frequency of the induced current, characteristics of the heat-piece, inductor design and favourable temperature range. Higher resistivity of the heat-piece gives better heating. Smaller gaps between the coil and the heat-piece result in higher induction heating efficiency. Also, the skin effect dictates that the induced current density is highest on the surface and falls exponentially away from the surface. Penetration depth quantifies the distance at which the current density falls to 1/e times the surface value. The penetration depth depends on the frequency of AC, relative magnetic permeability and electrical resistivity of the heat-piece [59].

A vessel made of enamelled cast iron gave the highest energy efficiency in the study of Villacís et al. [61], compared to stainless-steel and aluminium. They also noted that a wider gap between the vessel bottom and the stovetop results in lower energy efficiency. Acero et al. [62] found that using litz wire, ferrite, and ferromagnetic loads could result in induction efficiencies higher than 95%. Ferrites improve the coupling between the windings and the vessel. These ferrites are generally placed on an aluminium foil to isolate the electronics beneath the inductor assembly. Non-ferromagnetic loads gave induction efficiencies lower than 70%. A study by Prist et al. [63] proposed an induction cookstove with an automatic temperature control system using a PID controller. The active temperature control was based on the water temperature in the water boiling test and could achieve 22% energy savings. A thermal model and temperature control algorithm were first developed in the simulation environment and later tested using hardware.

4.2.2. Resistive cooking

In resistive type electric heating, the electric current passes through a metal wire and generates heat owing to the high electric resistance and thermal conductivity of the wire (Fig. 8a). The wire turns red hot and emits thermal radiation. Three types of resistance heaters – resistance coil cooktops, infrared resistance cooktops and solid disk cooktops – involve different heat transfer mechanisms [64,65].

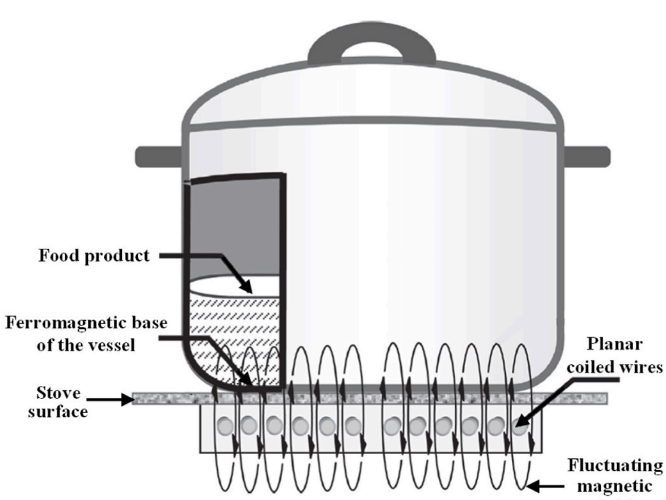

Fig. 7. Schematic of an induction stove showing the components (reprinted from Ref. [60] with permission from Elsevier).

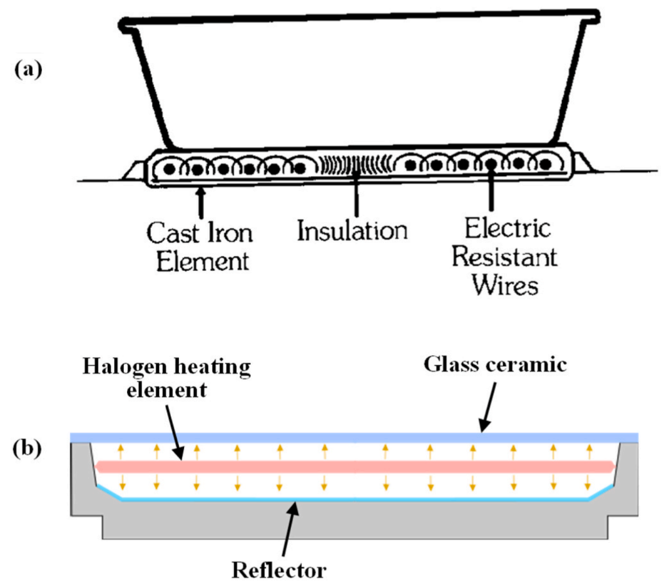

Fig. 8. Schematic of (a) electric resistance heating and (b) electric radiative heating [64].

1) In a resistance coil cooktop, the electric wire is enclosed in a metallic or ceramic sleeve filled with an insulating material. The sleeve is wound in the form of a coil. The hot wire heats the sleeve, and the sleeve heats the vessel by conduction. The sleeve is wound closely, and its surface is flattened to ensure good surface contact with the vessel [64,65]. However, closely wound coils and imperfections in the bottom of the vessel reduce the conduction heat transfer and the cookstove efficiency.
2) In an infrared resistance cooktop, the heating wire is placed below a glass-ceramic surface. The infrared radiation from the heating element heats the vessel placed over the glass surface. The high emissivity of glass allows radiation to pass through. Since glass has low thermal conductivity, heat conduction contributes only about 30% of the total heat transfer, resulting in localised heating of the glass surface [64,65].
3) In a solid disk cooktop, electric wires are enclosed in insulation and housed in a solid disk, usually cast iron (Fig. 8a). Heat is transferred to the vessel placed on the heated disk by conduction [64].

A study reports the temperature distributions in an infrared resistance cookstove using FEM modelling [66]. In a pyroceramic hot plate, the dependence of energy consumption on vessel size, power, heating zone diameter, the quantity of heated water and simultaneous use of multiple heating zones have been identified [67].

4.2.3. Radiative cooking

Radiative cooking consists of a halogen lamp placed below a glass-ceramic (vitro-ceramic) surface (Fig. 8b). The halogen lamp emits infrared radiation and heats the vessel placed on the glass surface. Reflectors at the bottom of the cookstove direct the infrared radiation towards the vessel. During operation, the lamp produces a reddish light visible through the glass surface [64]. The vitro-ceramic glass surface transmits about 80% of the infrared rays and absorbs visible light. Radiation heat transfer to the vessel exceeds heat conduction through the glass surface [68].

4.2.4. Other studies

Svosve and Gudukeya [69] developed an electric cookstove with two intelligent functions - one, it automatically switches off if no vessel is kept on the hotplate for a duration of 5 min. Second, it detects if the food starts to burn based on the water content remaining in the vessel. Though the stove is turned off immediately after sensing the food burning, the plate would require 15–20 min to cool from 280 °C to 50 °C, which would not prevent the food from burning. Thus, a mechanical system was incorporated to move the heating plate away from the vessel when burning was detected. A study by Ghelli et al. [70] proposed a fuzzy logic-based system suitable for integration with any electric stove. This system makes the electric stove semi-autonomous, energy-efficient, safe and smart. The system could control the stove for the common cooking processes, namely boiling, stir/shallow frying, deep frying and warming. The semi-autonomous cookstove achieved average energy savings of 21.42% while boiling, 34.43% while stir/shallow frying and 20.29% while deep frying in comparison to manual operation by the users. Based on long-term energy system modelling, Yangka and Diesendorf [71] estimated that promoting electric cooking in Bhutan could reduce kerosene consumption by 1832 kL and fuelwood by 55 kilotonnes yearly. This leads to overall reductions in the emission levels of CO_2 (17%), SO_2 (12%) and NO_x (8%). However, these benefits are likely to elevate the electricity demand by 9.1%.

4.2.5. Comparison

Two resistance electric cookstoves, an induction hob and an electric pressure cooker (Fig. 9a and b), have been compared by Aemro et al. [72]. The energy efficiency measured by boiling water was the highest with the electric pressure cooker at 78.8%, followed by 70.5% with the induction hob, 67.5% with the single hot plate and 32.6% with the local resistance cookstove. Correspondingly, the energy cost was highest with the local resistance stove. Induction cookstove is more efficient since it generates heat in the vessel, whereas resistance cookstove generates heat in the coil and then transfers it to the vessel. The imperfect contact between the resistive coil and the vessel bottom reduces the conduction heat transfer. The pressure cooker could save about 59.4% of energy compared to the local resistance stove. If a rural household shifts from a local cookstove to the single hot plate stove, US$41.83 could be saved per lifespan of the stove (8 years).

Induction cookstoves were more energy-efficient than resistance coil and infrared resistance cooktops, as reported by Livchak et al. [65] and Hager and Morawicki [60]. Slavova and Marinova [73] reported that a cast iron hot plate consumes more energy and is less efficient than a pyroceramic hot plate. Energy consumption was the lowest with the induction hob as its efficiency was maximum at 83.8%. Sadhu et al. [74] presented a comparison of induction and microwave cooking in terms of their operating principle, advantages and disadvantages. Since microwave provides heating by continuous realignment of dipolar water molecules in the food, the modified molecular structure of the food can cause serious health hazards. Though induction cooking offers a safer alternative that avoids such health hazards, its efficiency (90%) is slightly lower than a microwave oven (95–98%).

4.2.6. Summary of electric cookstoves

Electric cookstoves consist of induction, resistance and radiative types of heating. Induction cookstoves offer safe and efficient cooking, and the induction efficiency can be improved using a litz wire coil and ferrites [62]. Electric resistance cooking is less energy efficient due to higher heat losses compared to induction cooking. An energy efficiency of 83–86% was observed with the induction cookstove [65]. Manual or automatic power control results in lesser energy consumption. Electric cooking reduces the emissions of CO_2, SO_2 and NO_x significantly. Table A. 2 summarises the studies on electric cookstoves.

4.3. Hybrid cookstoves

A hybrid cookstove utilises multiple sources of energy to heat the cooking vessel. The literature documents a few cookstoves that combine solar energy with fuels (LPG, biomass) and electricity. These studies are discussed in the following sub-sections.

4.3.1. Solar-combustion hybrid

Prasanna and Umanand [75,76] presented a hybrid solar-LPG system that permits indoor cooking. A circulating fluid transferred heat from the solar collector to a buffer tank storage and from the storage tank to the cooking load (Fig. 10). The authors found the maximum power output by choosing the optimal pipe diameters and dynamically adjusting the flow rates using a maximum power point tracking (MPPT) controller. The proposed system performed on par with a standalone LPG cookstove, enabling cooking at any time and similar cooking duration. Since the circulating fluid heats the vessel, this system can be coupled with any burner without any modifications to the burner.

Mekonnen and Hassen [77] proposed a combination of solar energy

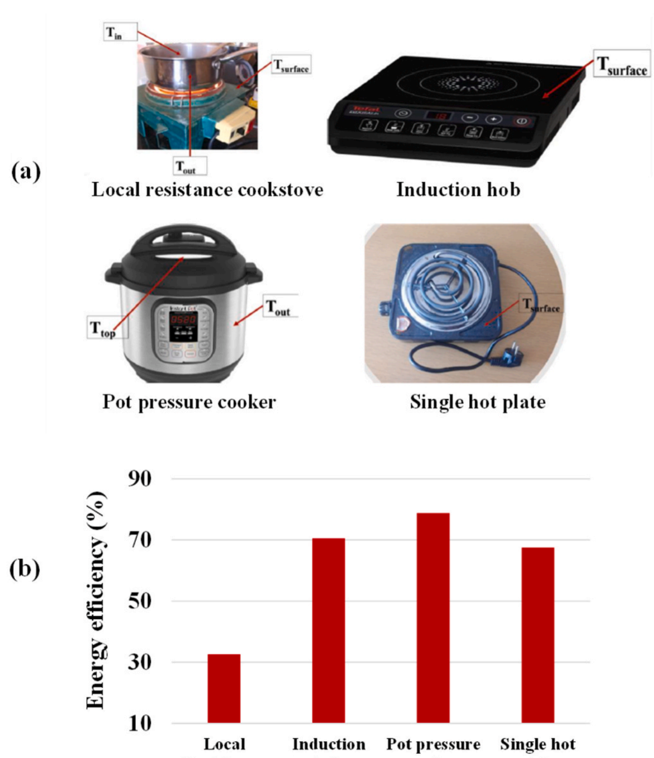

Fig. 9. (a) Electric cookstoves studied by Aemro et al. [72] and (b) their energy efficiency measured while boiling water. Two resistance cookstoves, an induction cookstove and an electric pressure cooker, have been compared (reprinted from Ref. [72] with permissions from Elsevier).

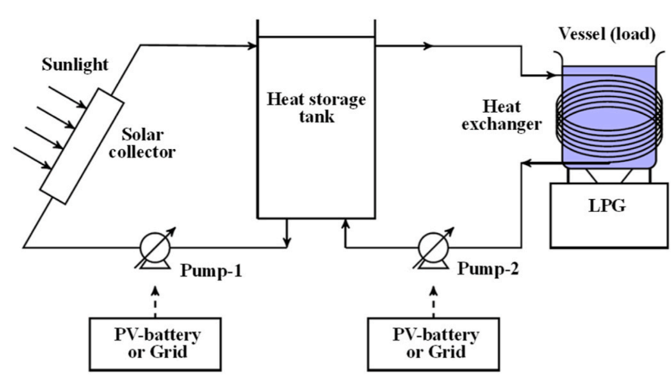

Fig. 10. Schematic of the hybrid solar-LPG system for cooking (reprinted from Ref. [75] with permission from Elsevier). The pumps drive a circulating fluid to transfer heat from the solar collector to the cooking load with an intermediate tank for energy storage.

with a biomass cookstove. In addition to the hot gases from biomass combustion, a box-type solar cooktop also contributed to vessel heating (Fig. 11). While the hot gases heated the vessel bottom, the solar radiation heated from the top. The hybrid stove gave a 5% improvement in thermal efficiency, and the fuel consumption was 6 g/l lower than a standalone biomass stove. A forced draft of air can be provided in biomass cookstoves using a solar-powered fan [78]. Kaundal et al. [79] recommended solar heating to supplement gasification-based biomass cookstoves. Concentrated solar energy can preheat the fuelwood to eliminate moisture content, thereby improving combustion. Properly designed solar heating can also accomplish the pyrolysis of fuelwood. Either direct solar heating through an optical window or indirect heating by means of a molten salt jacket around the cookstove can be incorporated to achieve fuel savings.

4.3.2. Solar-electric hybrid

A solar box-type cookstove has been coupled with a 10 W fan and a 200 W halogen lamp by Saxena and Agarwal [81]. The fan blows air around the halogen lamp, and the hot air is directed into the box cookstove through a trapezoidal air duct (Fig. 12). The cooking vessel is placed on lugs made of hollow copper balls to enhance the contact area between the vessel surface and the hot chamber air. With the forced flow of hot air, the thermal efficiency was 45.11%, and cooking power was 60.2 W, against 38.1% and 55.31 W, respectively, without the hot airflow. Among several studies focusing on electric cooking fed by solar PV panels [82–87], Joshi and Jani [88] presented an Improved Small Scale Box-type Hybrid solar cooker (ISSBH) consisting of five photo-voltaic panels (15 W each), a battery and three rod-type dc heaters (25 W each). This cookstove incorporated direct solar heating and electric heating from the rod heater powered by the PV panels and the battery. During the outdoor test, the water temperature reached the boiling point in 40 min, and the efficiency was 38.1%. Whereas during the indoor test, where direct solar heating is cut off, the time for boiling was 70 min, and efficiency was 36.4%.

Based on a techno-economic assessment, Dufo-Lopez et al. [89] suggested an off-grid photo-voltaic (PV) system along with an electric cookstove as a suitable alternative to traditional biofuels due to its cost reduction potential. A PV-battery system optimised to facilitate cooking

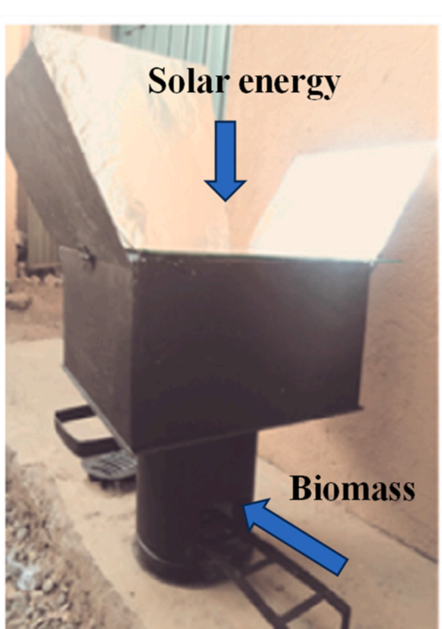

Fig. 11. Solar-biomass hybrid cookstove. Box-type solar cooktop reflects sunlight from the top, and hot combustion gases heat the vessel from the bottom (reprinted from Ref. [80] with permission from Taylor and Francis).

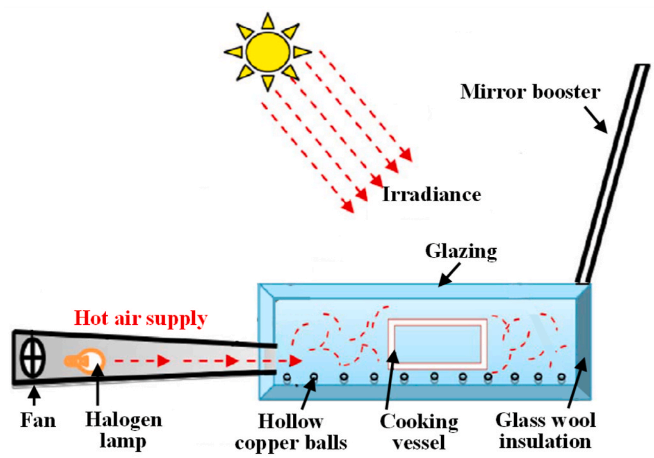

Fig. 12. Schematic of a Solar-electric hybrid cookstove (hybrid solar box cooker). The additional duct houses a 10 W fan and a 200 W halogen lamp. Hot air blown into the cookstove promotes vessel heating (reprinted from Ref. [81] with permission from Elsevier).

for 50 persons could cost less than 3 Euros per week per family and a life cycle emission of about 7gCO_2 per meal. Based on a multi-criteria decision analysis (MCDA), Batchelor et al. [90] identified Eastern and Southern Africa as suitable for quickly adopting battery-supported electric cooking fed by a photo-voltaic array (PV-eCook).

Topriska et al. [91] proposed a hydrogen production unit using an electrolyser powered by a solar PV panel to feed a Jamaican hydrogen cooker. A proton exchange membrane (PEM) electrolyser produces hydrogen that is stored in a metal hydride tank ($LaNi_5$) at an average pressure of 10 bar to ensure safe, low-pressure storage. A semi-empirical numerical model of the designed system considered the case study of an average Jamaican household. The model showed a daily demand of 1.98 kWh per household, translating into 1.7 kg hydrogen for a 60% efficient cookstove. Hydrogen production in the Jamaican climate was sufficient not only to meet the demand but also for backup. Topriska et al. [92] further evaluated the feasibility of a solar-hydrogen system based on the domestic cooking demands in Ghana, Jamaica and Indonesia. The numerical model calculated the hydrogen production rates, considering the weather data from each country. Solar hydrogen potential maps indicated that Ghana includes areas with a higher potential of 4–6 kWh/m^2/day than the other two.

4.3.3. Summary of hybrid cookstoves

The literature consists of only a few studies on hybrid cookstoves that utilise multiple sources of energy to heat the vessel. Solar cookstoves offer zero operating cost; however, their long cooking durations (lower power output) make them less preferred as a standalone alternative. Thus, solar energy has been coupled with other energy sources like LPG, biomass and electricity to improve the overall cookstove performance. Concentrated solar energy can completely demoisturise biomass before combustion. Solar-electric hybrid cookstoves either utilise electricity from the grid or use PV panels to generate electricity, which is used for electric heating or blowing hot air into box solar cookstoves. Table A. 3 summarises the studies on hybrid cookstoves.

4.4. Comparison of cookstoves

Hager and Morawicki [60] suggested comparing the total system efficiency of cookstoves powered by different energy sources rather than the device efficiency. The total system efficiency was defined as the product of production/transfer efficiency and the cookstove efficiency. The end-use efficiency is the highest with electric cookstoves (~80%) and very low with solar cookstoves (~20%), as shown in Fig. 13. Recent advancements in solar cookstove technology have shown better

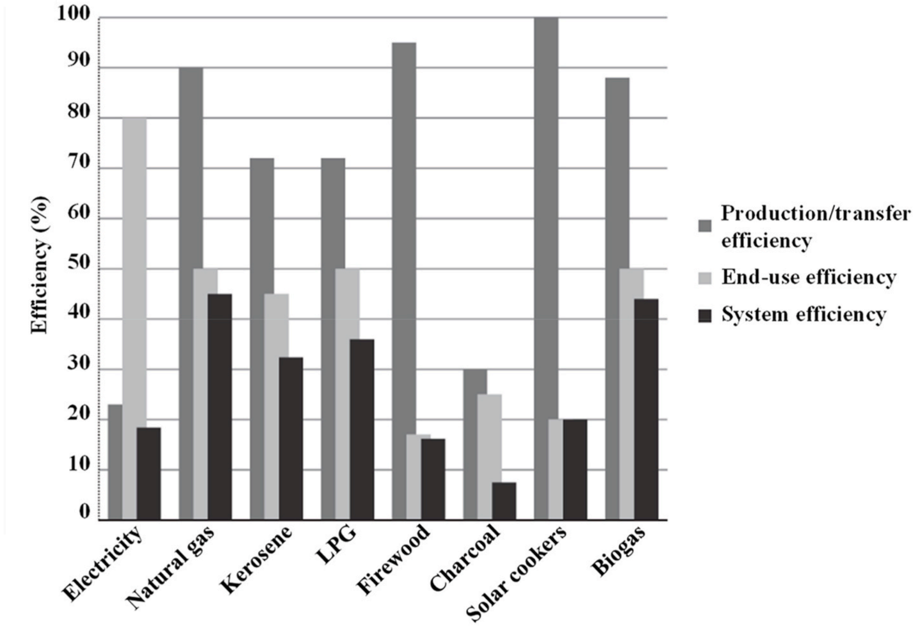

Fig. 13. Efficiencies of Production/transfer, end-use and total system efficiency with various fuels (reprinted from Ref. [60] with permission from Elsevier). Total system efficiency = (Production/transfer efficiency) * (End-use efficiency).

efficiencies up to 35–40% with direct solar cookstoves [25,28,40] and 63–69% with indirect solar cookstoves [53,54]. Electric cooking offers a low total efficiency due to the low production/transfer efficiency of electricity. However, solar cooking has the same total system efficiency as its end-use efficiency since its production/transfer efficiency is 100%. Despite these advantages, the useful thermal power of solar cookstoves (~200 W) is lower than electric and combustion cookstoves (1–2 kW) due to the low solar radiation input.

Livchak et al. [65] reported that induction cookstoves offer higher energy efficiency and faster temperature response than electric resistance and gas cookstoves. Boiling of water revealed maximum efficiencies of about 86% with the induction cookstove, 79% with the resistance stove, and 32% with the gas stove. High thermal loss from the gas cookstove flame makes it the least efficient. The electric resistance stove involves heat loss to the cookstove due to its higher thermal mass, whereas the induction stove minimises heat loss by generating heat in the vessel. Karunanithy and Shafer [93] also reported that energy efficiencies are highest with induction cookstoves, followed by electric resistance and natural gas stoves.

5. Overall summary and recommendations for future research

5.1. Main findings

Domestic cooking is an essential part of living that consumes considerable energy. The heat required for cooking is supplied by cookstoves that enable vessel heating. This paper presents for the first time an elaborate review of solar, electric and hybrid cookstoves. After a brief discussion of the cookstove performance testing, a summary of solar, electric and hybrid cookstoves has been presented. Solar cookstoves provide clean and cost-free operation, but they depend on sunlight availability and usually have longer durations of cooking due to low operating power. Direct-type box- and concentrating solar cookstoves can cook only outdoors, but indirect cookstoves enable indoor cooking by means of a heat transfer fluid. Electric cookstoves offer clean and efficient operation. However, off-grid and rural areas lack a continuous supply of electricity. Hybrid cookstoves utilise multiple sources of energy to heat the cooking vessel.

5.2. Comparison of various technologies

A comparison of all these cookstoves is also discussed, which shows the highest energy efficiency of 86% with an electric induction cookstove [65]. Total system efficiency, which includes the efficiencies of energy production, transportation and end-use, is a better indicator of the cooking life cycle. Electric cooking depicts low total system efficiency despite having the highest end-use efficiency (about 80%) since the efficiency of electricity production and transportation is low. In contrast, the total system efficiency of solar cooking equals its end-use efficiency. Recent advancements in solar cookstoves have shown efficiencies up to 35–40% with direct and 63–69% with indirect solar cookstoves.

5.3. Conclusions and recommendations for future research

Under solar cookstoves, the shape and size of box-type cookstoves limit the vessel size, and the vessel geometry may affect the heat transfer to the vessel. Future studies may focus on optimising the vessel size for maximum heat transfer. Adding solar concentrators and incorporating a microporous absorber plate surface in box-type solar cookstoves improve the cookstove performance. Solar-selective coatings enhance the absorptivity of collectors and may be utilised in future studies to harness solar insolation better [94]. Thermal energy storage using phase change materials can facilitate night cooking. An indirect cookstove that uses a nanofluid as a heat transfer fluid has shown better performance. Future studies may consider incorporating a PCM for thermal storage in addition to the nanofluid as the heat transfer fluid to improve the cookstove performance further. The thermal conductivity and specific heat of PCMs could be enhanced using novel techniques, such as the addition of nanomaterials and encapsulation [20]. The use of PCM for thermal storage in solar cookstoves needs economic evaluation to ensure the widespread adoption of improved technologies. Research focusing on developing low-cost and good-performance solar cookstoves needs to be carried out. Like the indirect solar cookstoves, the widely used solar water heaters also consist of solar collectors that transfer heat to the water directly or indirectly through a working fluid [94]. These solar water heaters use all the solar energy to heat water without considering the hot water requirement of the household. Thus, a combined water heater-cookstove system may be envisaged wherein the working fluid may be diverted to the indoor cookstove or the water storage based on the requirement. Such a system may find faster dissemination since solar water heaters are prevalent.

Electric cookstoves work on either induction heating, resistance heating or radiative heating. Induction cookstoves offer safe and efficient cooking, and the induction efficiency can be improved by using a litz wire coil and ferrites [62]. Electric resistance cooking is less energy efficient compared to induction cooking due to higher heat losses. Incorporating a manual or an automatic power control results in lesser energy consumption.

Few studies on hybrid cookstoves have combined solar energy with fuels (such as biomass and LPG) and electricity and observed better performance than solar cookstoves. Future studies may develop robust hybrid designs capable of competing with existing popular technologies. For instance, a solar-electric hybrid cookstove could be explored that senses sunlight availability and adjusts the electrical input to provide the desired heating. Future research could explore a hybrid of the solar water heater-cooking system suggested above with an electric or gas-fuel cookstove to ensure the desired heating, especially during no sunlight. If successfully disseminated, such hybrid cookstoves can significantly reduce fuel/energy consumption owing to the renewable solar component. Limited studies on hybrid cookstove technology call for future research attention towards developing sustainable cookstove technologies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix A. Tables of cookstove data

Table A 1

Summary of selected studies on solar cookstoves reviewed in this article (*Notation and acronyms:* F_1 - First figure of merit, F_2 - Second figure of merit, $T_{p,s}$ - stagnation temperature of the absorber plate, η - Energy efficiency, η_{ex} - Exergy efficiency, T_w - maximum temperature of water, PCM - Phase change material, TES - Thermal Energy Storage, HTF - Heat Transfer Fluid)

Paper	Cookstove/Collector type	TES/HTF	Useful thermal power (W)	Maximum efficiency	Description of the study and comments	Varied parameters
				Direct solar cookstoves		
[21] Mahavar et al., 2012	Box type	–	103.5 W (initial) 30 W (standardised)	F_1: 0.116 m^2K/W F_2: 0.466 $T_{p,s}$: 144 °C	**Box type - Single Family Solar Cooker (SFSC)** Theoretical analysis and Experimental testing to design the SFSC ***IS 13429:2000***	Cooking test on various food items
[22] Amer 2003	Box type	–	–	$T_{p,s}$: 165 °C	**Box type - Double exposure cookstove** Numerical prediction (Runge Kutta method) and experiments; Comparison of conventional and double exposure stoves	Sunlight exposure - single and double, test type - stagnation, transient and cooking tests
[23] Mirdha & Dhariwal 2008	Box type	–	–	$T_{p,s}$: 165 °C [1]	**Box type - improved design** Theoretical calculations and experiments; Comparison of conventional and improved design[1] with improved design; approximate value from plot	Booster mirror arrangement and orientation
[24] Ukey & Katekar 2019	Box type	–	19.767 W 49.639 W (standardised)	F_1: 0.3027 m^2K/W F_2: 0.607 η: 38.36%	**Box type - Octagonal cookstove** Experiments; Comparison of conventional and octagonal types ***IS 13429:2000***	Stove type
[26] Harmim et al., 2013	Box type/ compound parabolic concentrator (CPC)	–	78.9 W (standardised)	F_1: 0.152 m^2K/W [2] F_2: 0.470 [2] $T_{p,s}$: 166 °C	**Box type - building integrated type cooker with CPC reflector** Experimental analysis[2] without CPC reflector	Test type - stagnation, water heating and cooking tests
[29] Sagade et al., 2020	Box type	–	–	$T_{f,max}$: 152.2 °C (Max load temp)	**Modified cooking pot with glass lid** Experimental analysis	Pot lid - metallic and glass
[30] Ghosh et al., 2017	Box type	–	–	F_1: 0.09 m^2K/W [3]	**Box type - with modified glass covering** Experimental analysis[3] with evacuated glass with surface glazing	Three Glass covers: low-e IAO coated, uncoated double glaze, evacuated double glaze
[27] Harmim et al., 2010	Box type	–	–	$T_{p,s}$: 140 °C [4]	**Box type - with finned absorber plate** Experimental analysis[4] approximate value from plot	Absorber plate: with and without fins
[31] Cuce and Cuce 2015	Box type	–	–	η: 30%[5] η_{ex}: 6%[5]	**Box type - with finned absorber plate** Theoretical analysis[5]	Absorber plate: with and without fins Seasons: Summer and winter

(continued on next page)

Table A 1 (*continued*)

Paper	Cookstove/Collector type	TES/HTF	Useful thermal power (W)	Maximum efficiency	Description of the study and comments	Varied parameters
					with finned absorber plate in summer	
[25] Cuce 2018	Box type	–	15.4 W *	η: 34.6%[6] η_{ex}: 22.6%[6]	**Box type - with microporous absorber surface** Mathematical and experimental analyses [6] with trapezoidal microporous absorber surface	Microporous absorbers: triangular, semi-circular and trapezoidal porosities
[28] Cuce 2018	Box type	TES: Bayburt stone	–	η: 35.3%[7] η_{ex}: 21.2%[7]	**Box type - with thermal storage along the cookstove walls (Bayburt stone)** Experimental analysis[7] with Bayburt stone thermal storage	Thermal storage: with and without Bayburt stone
[32] Coccia et al., 2020	Box type	TES: Erythritol PCM	–	F_1: 0.19 m^2K/W η: 25%	**Box type - with PCM thermal storage in the cooking vessel** Experimental analysis	With & without PCM Tests with no load, water, silicone
[33] Farooqui 2013	Box type	–	–	F_1: 0.1258 m^2K/W F_2: 0.369	**Box type - with gravity-based sun tracking** Experimental and numerical analysis	—
[34] Al-Soud et al., 2010	Concentrating type/ Parabolic trough collector	–	–	T_w: 90 °C	**Parabolic type - with two axes automatic sun tracking** Experimental analysis	—
[35] Abu-Malouh et al., 2011	Concentrating type/ Spherical dish collector	–	–	T_w: 93 °C	**Spherical type - with two axes automatic sun tracking** Experimental analysis	—
[38] Indora & Kandpal 2018	Concentrating type/ Parabolic dish & Scheffler collector	–	–	–	**Concentrating & Scheffler type - Techno-economic assessment**	—
[40] Onokwai et al., 2019	Concentrating type/ Parabolic dish collector	–	–	η: 44.2% η_{ex}: 41.3%	**Parabolic type - redesigned** Theoretical prediction and experimental analysis	Tests with no load and with water
[41] Ahmed et al., 2020	Concentrating type/ Parabolic dish collector	–	–	T_w: 74.5 °C	**Parabolic type – redesigned material** Experimental analysis	Reflective material – stainless-steel, aluminium foil, mylar tape
[42] Goswami et al., 2019	Concentrating type/ Parabolic dish collector	–	63 W	η: 21.91% η_{ex}: 23.11%	**Parabolic type** Experimental analysis	Cooking pot – with and without coating of activated carbon
[44] Chaudhary et al., 2013	Concentrating type/ Parabolic dish collector	TES: Acetanilide	–	–	**Parabolic type - with PCM thermal storage in the cooking vessel** Experimental analysis	Cooking vessel – with and without black painted surface
[45] Gallagher 2011	Concentrating type/ Flat mirror segments (parabolic, umbrella, conical shapes)	–	~640 W	–	**Parabolic type - Solar fryer for cooking Injera bread** Experimental analysis	–
[46] Nazari et al., 2020	Concentrating type/ Parabolic dish collector	–	–	–	**Concentrating type - Solar bread cooker** Experimental analysis & AI hybrid model	Cooking plate position, cooking duration, protective edge, insulator cap, weather condition
[43] Hosseinzadeh et al., 2020	Concentrating type/ Parabolic trough collector[8]	–	60–179 W	η: 75.6%[9]	**Evacuated tube type - to boil water** Experimental & analytical analysis [8] Can only boil water filled in an evacuated tube [9] from data in tables	Pressure of vacuum envelop, absorptivity & emissivity of the absorber coating, solar radiation

Indirect solar cookstoves

Paper	**Collector Type**	**TES/HTF**	**Useful thermal power (W)**	**Maximum efficiency**	**Comments**	**Varied parameters**
[36] Valmiki et al., 2011	Fresnel lens collector	HTF: Mineral oil	–	T_p: 300 °C[10] & 150 °C[11]	**Fresnel lens type - for indoor cooking** Experimental analysis [10] stovetop temperature outdoor [11] stovetop temperature indoor	—
[47] Hussein et al., 2008	Evacuated tube with heat pipe, absorber plate & reflectors	HTF: Degassed distilled water TES: Magnesium nitrate hexahydrate PCM	72–420 W	T_w: 100 °C	**Flat plate type - with PCM and indoor cooking** Experimental analysis	With and without cooking load
[51] Esen 2004	Evacuated tube with heat pipe	HTF: R-134a, R–407C, R-22 TES: Mobiltherm 605 oil	–	T_w: 97 °C	**Evacuated tube type - with PCM and indoor cooking** Experimental analysis	HTF used in heat pipe - R-134a, R–407C, R-22

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Table A 1 (*continued*)

Paper	Cookstove/Collector type	TES/HTF	Useful thermal power (W)	Maximum efficiency	Description of the study and comments	Varied parameters
[48] Nayak et al., 2016	Evacuated tube with heat pipe	HTF: Water TES: Stearic acid, Acetanilide PCM	–	η: 31%[12]	**Evacuated tube type - with PCM and indoor cooking** Experimental analysis [12] with acetanilide PCM	PCM material - Stearic acid, acetanilide
[52] Singh et al., 2015	Evacuated tube	HTF: Water, thermal oil TES: Acetanilide PCM	–	–	**Evacuated tube type - with PCM and indoor cooking** Experimental analysis	HTF - Water, thermal oil heat Gate valves open/close during PCM discharge
[37] Farooqui 2015	Single vacuum tube with plane mirror strip reflectors	HTF: thermal or vegetable oil	–	η: 25% η_{ex}: 3.8%	**Single vacuum tube type** Experimental analysis	Water load (3–7 kg)
[53] Hosseinzadeh et al., 2021	Parabolic dish collector	HTF: thermal oil, MWCNT oil[13]	113–182 W (average)	η: 69% [14], 20%[15] η_{ex}: 44%[14], 2%[15]	**Parabolic type - with nanofluid HTF** Experimental analysis [13] MWCNT: multi-walled carbon nanotube [14] for cooking unit,[15] for collector and cooking unit	HTF - thermal oil, MWCNT[13] oil **nanofluid**
[54] Hosseinzadeh et al., 2021	Parabolic dish collector	HTF: thermal oil, SiO_2-, TiO_2- and SiC-oils	117–156 W (average)	η: 63%[16], 17%[17] η_{ex}: 42%[16], 1.8%[17]	**Parabolic type - with nanofluid HTF** Experimental analysis [16] for cooking unit,[17] for collector and cooking unit	HTF - thermal oil, SiO_2-, TiO_2- and SiC-oil **nanofluids**
[49] Singh 2021	Parabolic dish collector	HTF: Therminol 55 synthetic oil	–	η: 21% η_{ex}: 1.9%	**Parabolic type - with solar tracker charged by PV panel** Experimental analysis	—
[50] Wang et al., 2019	Fresnel lens collector with cavity receiver	HTF: Mineral oil	–	$\eta_{optical}$: 76.4%[18]	**Fresnel lens type** Optical simulation using Monte-Carlo Raytracing [18] Optical efficiency of cavity receiver	Receiver cone angle and reflectivity, receiver surface absorptivity
			Comparison of solar cookstoves			
Paper	**Collector Type**	**TES**	**Useful thermal power (W)**	**Maximum efficiency**	**Comments**	**Varied parameters**
[55] Panwar et al., 2013	Box & parabolic dish type	–	–	η: 60.94%[19] η_{ex}: 8.71%[19]	**Comparison of direct solar cookstoves** Experimental analysis [19] with Hot box cooker	Comparison of Hot Box, Animal Feed and Parabolic type cookstove
[18] Ozturk 2007	Box & parabolic type	–	8.2–60.2 W (box) 20.9–73.5 W (parabolic)	η: 35.2%[20] η_{ex}: 3.52%[20]	**Comparison of direct solar cookstoves** Experimental analysis [20] with box type cooker	Comparison of box type and parabolic concentrating solar cookstove
[56] Pandey et al., 2012	Box & parabolic dish collector	–	–	η_{ex}: 10.4%[21]	**Comparison of direct solar cookstoves** Experimental analysis [21] with paraboloid type cooker	Comparison of box type and paraboloid concentrating solar cookstove
[57] Mussard et al., 2013	Parabolic trough	HTF: Duratherm 630 oil TES: $NaNO_3$–KNO_3 melting salts	–	–	**Comparison of direct parabolic and indirect parabolic type solar cookstoves** Experimental and numerical analyses	Comparison of SK-14 direct parabolic type and parabolic trough type indirect cookstoves

Table A 2
Summary of studies on electric cookstoves reviewed in this article (*Notation*: η - Energy efficiency, η_{in} - Induction efficiency)

Paper	Efficiency/energy savings	Comments	Varied parameters
[61] Villacís et al., 2015	η: 80–94%[1]	**Energy efficiency measurement of induction cookstove** [1] ASTM F 1521-03 and NTE 2851 standard test	Pot material: stainless steel, cast iron, aluminum, Gap between stove top and vessel bottom, concavity/convexity of vessel bottom,
[62] Acero et al., 2013	η_{ind}: 95%[2]	**Analytical model & measurement of induction efficiency** [2] using ferrite, Litz wire, ferromagnetic pot material	Pot properties, ferrite arrangement, current frequency, type of cable (solid, Litz wire), number of turns
[63] Prist et al., 2018	22% energy savings	**Simulation, Hardware-In-Loop & experiments** Automatic temperature control using PID controller during Water boiling test	–
[65] Livchak et al., 2019	η: 83–86%[3]	**Performance comparison of electric cookstoves** [3] with induction stove	Cookstove type: Electric resistance ceramic, resistance coil, induction and gas burner
[66] Slavova et al., 2017	–	**FEM modelling of pyroceramic plate** Temperature distribution comparison	With & without load

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Table A 2 (*continued*)

Paper	Efficiency/energy savings	Comments	Varied parameters
[67] Slavova and Marinova 2020	η: ~85%[4]	**Experimental analysis of pyroceramic electric hot plate, induction hob, cast iron electric hot plate** [4] approximate value form plot (BS EN 60350–2:2018 standard)	Heating zone diameter, quantity of heated liquid, power input
[69] Svosve and Gudukeya 2020	–	**Electric cookstove prototype with two intelligent functions** Automatic switch on/off & physical motion of plate away from vessel if food burns	–
[70] Ghelli et al., 2015	21.4, 34.4, 20.3% energy savings[5]	**Fuzzy logic-based system – useable with any electric cookstove for energy efficient cooking** [5] during boiling, shallow frying & deep frying respectively	Cooking processes: boiling, shallow frying, deep frying, warming
[72] Aemro et al., 2021	η: 78.8%[6]	**Comparison of electric cookstoves: energy consumption, cost, efficiency, output/input** [6] with electric pressure cooker	Cookstove type: electric pressure cooker, induction hob, single hot plate, resistance cookstove
[73] Slavova and Marinova 2017	η: 84%[7]	**Comparison of electric cookstoves: energy consumption and efficiency** [7] with induction hob	Cookstove type: cast iron hot plate, pyroceramic hot plate, induction hob
[74] Sadhu et al., 2010	η: 95–98% [8]	**Comparison of induction and microwave cooking** [8] with microwave oven	–

Table A 3
Summary of studies on hybrid cookstoves reviewed in this article (*Notation and acronyms:* η - Energy efficiency, *PV* - Photo-voltaic)

Paper	Type of hybrid	Efficiency/energy savings	Comments	Varied parameters
[75,76] Prasanna and Umanand 2011	Solar-LPG	$\eta_{overall}$: 88%[1]	**Simulation & experiments** **Solar indirect heating + LPG burner** [1] collector to load efficiency	Fluid flow rates, pipe diameter
[77] Mekonnen and Hassen 2019	Solar-Biomass	η: 5% higher[2]	**Efficiency measurement** **Solar box-type + biomass rocket-type cookstove** [2] with solar-biomass cookstove compared to biomass cookstove	Operation type: Only biomass, only solar and combined solar-biomass
[79] Kaundal et al., 2018	Solar-Biomass	–	**Design of biomass cookstove with solar preheating**	Direct heating through solar collector and optical window, indirect heating through molten salt PCM
[81] Saxena and Agarwal 2018	Solar-Electric	η: 45.1%[3]	**Efficiency measurement** **Solar box-type stove + forced air flow through a halogen lamp** [3] with the hybrid solar box cookstove	With and without load
[88] Joshi and Jani 2015	Solar-Electric	η: 38%[4]	**Efficiency measurement** **Solar box-type cookstove + electric heater powered by solar PV panels** [4] with the hybrid stove in outdoor test	Indoor & outdoor testing
[91] Topriska et al., 2015	Solar-Hydrogen	–	**Numerical model & experiments** **Solar PV panel + Hydrogen production unit**	–

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