Energy Nexus 19 (2025) 100521

Contents lists available at ScienceDirect

Energy Nexus

journal homepage: www.elsevier.com/locate/nexus

Review Article

Advancing solar cooking: Challenges, innovations, and future directions

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1. Introduction

Solar energy has been a powerful resource, and its use for cooking food dates back to 1767 [1]. In the last century, solar cooking has been explored to fight against poverty in developing regions [2]. With the depletion of non-renewable energy sources and the need to minimise environmental impacts, solar energy for food cooking is gaining prominence, with new research needs being identified [3,4]. Solar energy also holds the potential to become a primary source for domestic and industrial applications.

Harnessing solar power for cooking is a sustainable, environmentally friendly practice that aligns with all 17 UN Sustainable Development Goals [5]. Notably, it significantly impacts Goal 2 (Zero Hunger) by contributing to the eradication of hunger and poverty in regions where solar cooking is feasible, Goal 7 (Affordable and Clean Energy) by promoting the use of sustainable energy, and Goal 13 (Climate Action) by reducing greenhouse gas emissions and preserving natural resources [6].

Despite the limitations of some solar cooker devices, such as their limited cooking capacity (as most solar cookers can only support one pot during cooking), solar cookers are designed to replace traditional cooking methods like baking, boiling, and frying [7].

Direct solar cookers are the most used and can be classified into three categories: parabolic, box, or panel models [8]. Under certain meteorological conditions, such as periods of low-intensity solar radiation, incorporating a thermal energy storage system with phase change material (PCMs), which absorb and release latent heat during phase transitions to help maintain cooking temperatures, is advantageous [9]. Performance parameters for solar cookers include energy efficiency, which refers to the ratio of effective heat transferred to the cooking vessel compared to the total solar energy received, and exergy efficiency, which considers the quality of energy conversion by accounting for entropy generation and irreversibility during heat transfer. Additionally, thermal performance is often evaluated using standardised metrics such as the first and second figures of merit (F_1 and F_2), which assess heat transfer efficiency under both loaded and unloaded conditions, and cooking power, which quantifies the rate of energy delivered to the food, typically measured under controlled conditions to compare different solar cooker designs [10,11]. Some international standards have been established to ensure consistent evaluation. However, there is a lack of research focused on designing solar cooking devices to optimise energy use and improve the quality of processed foods. While existing research has explored aspects such as solar cooker efficiency [12,13], socio-economic adoption challenges [14,15], and thermal storage materials [16], a comprehensive interdisciplinary study that integrates thermal performance, food quality, and AI-based modelling remains absent. This review provides a multidisciplinary perspective on solar cooking technologies, integrating aspects of thermal modelling, material science, and machine learning-driven optimisation. While not providing an in-depth technical evaluation of experimental procedures, this review critically analyses performance metrics and modelling approaches from the literature to highlight key research gaps and emerging opportunities to advance solar cooking efficiency and adoption.

Integrating mathematical modelling and simulation of heat and mass transfer phenomena with their impact on food quality could significantly advance this field [4].

Understanding the potential nutritional benefits of solar cooking can also drive consumer adoption. The thermal cooking process can enhance nutrient digestibility, improve protein quality, texture, and appearance of vegetables and legumes, and increase nutrient absorption. However, it may also lead to losing some vitamins and minerals [17]. Despite studies on the thermal performance of solar cookers [18,19], research on the impact of solar cooking on food quality, particularly in terms of nutrient retention and degradation kinetics, is still underexplored. Research on the modelling and simulating of time-temperature profiles and histories of real foods during solar cooking is scarce. Addressing these aspects and conducting experimental studies is crucial [20].

Predicting solar cookers' energy performance and food quality outcomes is complex due to numerous dynamic variables. Machine learning, a field of artificial intelligence, can address these challenges by using historical data to build predictive models. Once trained on a set of examples, these models can predict outcomes for new data [21,22]. Various paradigms, including Bayesian frameworks, margin

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https://doi.org/10.1016/j.nexus.2025.100521
Received 8 November 2024; Received in revised form 13 May 2025; Accepted 23 August 2025
Available online 24 August 2025

maximisation, and neural networks, have been proposed to train supervised models [23]. By applying machine learning, we can better predict and optimise the performance of solar cookers, enhancing their efficiency and the quality of cooked food.

This review addresses interdisciplinary challenges in solar cooking by integrating thermal performance analysis, sustainability, and food science perspectives into a unified framework. Unlike previous studies focusing on isolated aspects, this work provides a broader assessment, incorporating recent advancements in modelling techniques and AI-driven predictions. By synthesising insights from experimental studies and emerging computational methods, we evaluate the efficiency of solar cookers and their impact on food quality. Furthermore, this review explores the broader implications of solar cooking in sustainability, public health, and energy policy, reinforcing its role in achieving global energy transition goals. These insights contribute to optimising solar cooker designs, improve their usability, and fostering broader adoption in developing and developed regions.

In this review paper, the following key aspects are explored:

- Technological advancements in solar cooking, including various solar cooker designs and their efficiency.
- Current developments in solar energy-based cooking, with a focus on global trends and regional implementations.
- Integration of advanced materials, such as nanofluids and improved thermal storage techniques, to enhance performance.
- Modelling approaches and performance assessments, including experimental and theoretical evaluations.
- Economic, social, and policy considerations for adopting and scaling solar cooking technologies.

2. General classification of solar cookers

There are different types of solar cookers, each with its own design and advantages based on their geometry and construction materials, making them suitable for various needs [24]. They can be classified into two types: direct and indirect, depending on how thermal energy from the sun is transferred to the cooking pot [25]. In indirect solar cookers, the solar energy is used to generate or transfer heat indirectly to the cooking vessel. A general classification is presented in Fig. 1.

As illustrated in Fig. 1, solar cookers can be categorised based on three primary aspects: cooking method, structural type, and thermal storage. Regarding cooking methods, solar cookers can be classified as either direct or indirect, depending on how solar energy is transferred to the cooking vessel. The structural type further divides solar cookers into three categories: parabolic, box, and panel, each with distinct designs and efficiency levels. Finally, the thermal storage mechanism used in solar cookers plays a crucial role in their performance, including sensible heat storage (storing heat in materials like water or stone) and latent heat storage (utilising phase change materials for prolonged heat retention). This classification provides a systematic approach to understanding the key features and operational differences among solar cookers, allowing for targeted improvements in efficiency and usability.

Each structural type presents distinct advantages and limitations that influence their suitability for different cooking applications.

Parabolic solar cookers, featuring concave bowl-shaped reflectors, efficiently generate high temperatures, reducing times for boiling water and cooking food [26,27]. Adjustable and sun-orientation-dependent, they require constant alignment for optimal performance [28]. Factors like dish size, solar radiation intensity, reflectivity, and geometry influence their cooking efficiency [16,19,29,30]. Despite its benefits, ongoing monitoring is crucial to prevent fire risks and ensure stability and heat retention in windy or cloudy conditions [16,30].

Box-type solar cookers efficiently utilise direct sunlight to heat the pot, comprising an insulated box with a transparent cover, reflective surfaces, and an adjustable booster mirror for intensified solar radiation [31,32]. Particularly effective at higher latitudes, the booster mirror enhances energy absorption. Optimisation of each component is essential for maximum efficiency and cooking power. The absorber tray facilitates effective solar energy transfer, and thermal efficiency is influenced by the number of cooking pots [9]. While these cookers heat slowly, adding a heat conservation system extends cooking times during low radiation, allowing effectiveness in diverse weather conditions [8].

Panel solar cookers, known for their simplicity and affordability, employ a basic design with affordable materials. They come in various shapes and contain an aluminium foil reflective surface enclosed in a clear plastic cover [8]. Primarily functioning as slow cookers with limited cooking power, these portable devices concentrate sunlight from above onto the cooking pot, reducing efficiency [33]. Despite this drawback, people who live or travel alone appreciate panel solar cookers for their easy transportability [8].

Parabolic solar cookers typically achieve geometric concentration ratios (CR_g) between 20 and 200, reaching temperatures exceeding 300 °C. In contrast, box cookers with multiple reflectors can achieve CR_g values up to 10, with temperatures generally ranging between 140 and 180 °C, depending on insulation and absorber efficiency [34]. In addition to the geometric concentration ratio, the optical concentration ratio (CR_o) considers reflectivity and angular losses, while the effective concentration ratio (CR_{eff}) accounts for overall system efficiency under real conditions, including optical and thermal losses [35]. These indicators allow for realistic performance comparison between different designs. Furthermore, the Cooker Opto-Thermal Ratio (COR) has been proposed as a reliable index for comparing both low- and high-temperature cookers under variable conditions. COR consolidates optical and thermal behaviours and is increasingly used as a universal indicator of cooker performance [36,37]. These distinctions are essential for evaluating and comparing solar cooker performance and guiding design improvements.

Beyond these factors, the thermal performance of solar cookers is

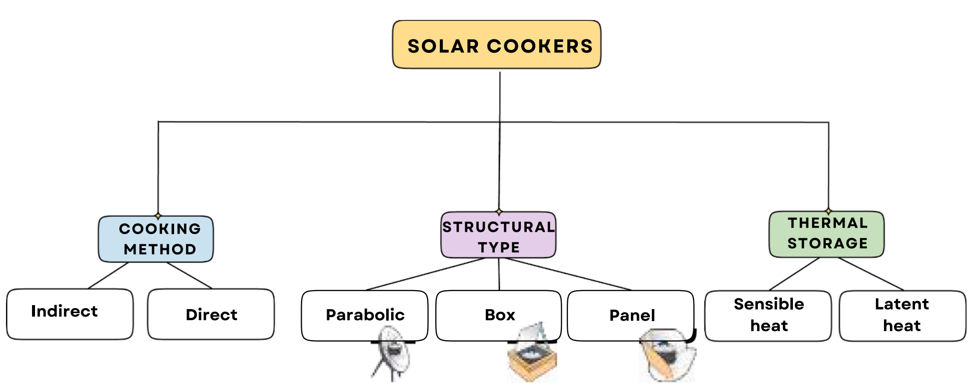

Fig. 1. A general classification of solar cookers.

also influenced by the material and optical properties of the cooking vessel. Dark, non-reflective surfaces, such as anodised aluminium and black-coated stainless steel, enhance heat absorption and minimise radiation losses, improving overall efficiency [12,36,38].

For solar cookers to truly replace conventional cooking methods, they must meet three crucial criteria: affordability, practicality, and the ability to reach high temperatures. Deep knowledge gained from studying the thermal performance of each cooker is essential to achieve these goals.

3. Current developments in solar cooking technology research

The analysis of solar cooking research over the past 24 years (January 2000–May 2024), as documented in the Scopus database [39], reveals a growing interest in this field (Fig. 2). Approximately 900 publications have been published, with a noticeable increase in recent years, reflecting a rising awareness and academic focus on the potential and benefits of solar cooking. The temporal distribution of publications indicates a gradual but constant increase in the number of studies related to solar cooking. The early 2000s saw a modest number of publications, but since 2010, there has been a significant upward trend, peaking in 2023 with 102 publications. This trend highlights the growing recognition of solar cooking's importance in addressing energy sustainability and environmental impact.

Geographical analysis shows that India leads in solar cooking research, contributing almost 40 % of the total publications, followed by the United States and Mexico, with approximately 7 % and 5 %, respectively. This distribution points to a global interest in solar cooking across developed and developing countries, as defined by the United Nations [40]. Specifically, developing countries contribute 76 % of the research, while developed countries account for 24 %. The increasing participation of developed countries, such as the United States and the United Kingdom, underscores a broader acceptance and exploration of solar cooking technologies beyond regions traditionally dependent on alternative energy solutions.

This review considers studies up to May 2024 to ensure a comprehensive assessment of the most recent advancements in solar cooking technology, particularly in efficiency improvements, automation, and material innovations. As demonstrated in Fig. 2, research interest in this field has grown significantly in recent years, necessitating an up-to-date analysis to capture current trends and emerging developments accurately.

Further analysis using VOS viewer 1.6.20 [41] examined research patterns over the last ten years by studying the co-occurrence of 118 keywords that appeared at least 15 times across all papers. This analysis identified four distinct clusters, as illustrated by different colours Fig. 3**a)** Cluster distribution of the recently published information on solar cooking between 2014 and 2024, and **b)** Time analysis of cluster distribution. By analysing the frequency and relationships between keywords, VOS viewer provided insights into the major themes and trends within the research field, allowing to visualise how various aspects of solar cooking are interconnected and where future research might be headed.

Following the identification of these clusters, the authors carefully analysed and characterized each group based on the prevalent keywords and themes. This detailed examination allowed the authors to name and define the clusters according to their core research areas. The following sections provide an overview of these clusters, highlighting their primary focus and contributions to the field of solar cooking:

1. Renewable Energy and Sustainable Development
   Renewable energy technologies and sustainable development are the main focus of this group. It covers solar energy systems, biomass, and photovoltaic cells, emphasising energy conservation, policy, and optimization, especially in developing countries. Key concerns include greenhouse gas emissions and carbon dioxide reduction, with practical applications in solar cooking systems.
2. Solar Cooking and Thermal Performance.
   This research focuses on solar cooking technologies and their thermal performance. It covers different types of solar cookers and components, such as mirrors and reflectors, emphasising efficiency metrics and experimental studies. The research cluster investigates the design, performance, and materials that impact the efficiency of solar cookers.
3. Thermal Energy Storage and Heat Transfer
   This research studies thermal energy storage and heat transfer, highlighting phase change materials (PCMs) and other storage media. It examines thermal properties, such as latent heat, thermal conductivity, and heat capacity, and includes simulations to optimize these systems. Solar thermal energy integration is also a key focus.
4. Exergy, Efficiency, and Climatic Conditions
   Exergy and energy efficiency are explored in different climatic conditions, focusing on experimental investigations and mathematical modelling. The practical applications include oils and fats, parabolic dishes, and water heating, demonstrating the importance of solar energy technologies in achieving efficiency and sustainability.

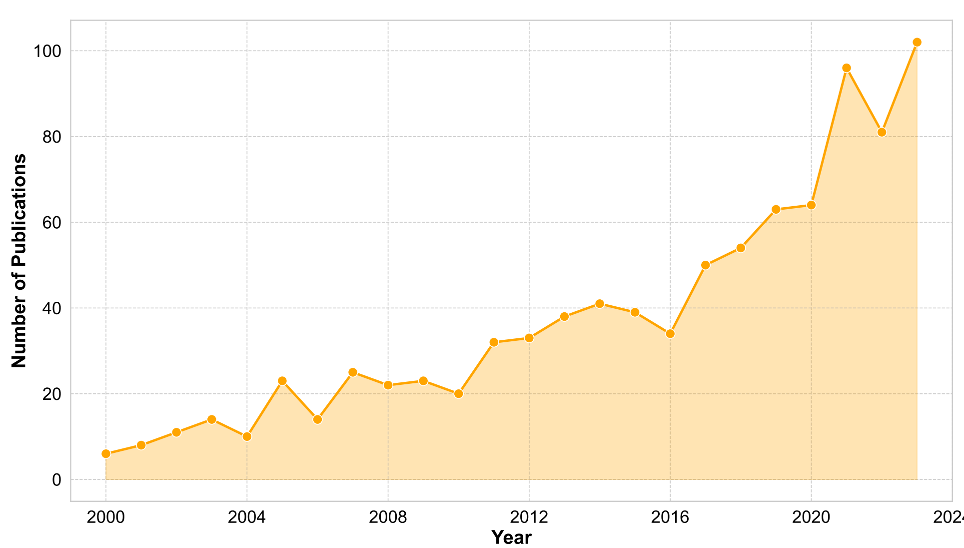

Fig. 2. Number of publications related to solar cooking studies vs year.

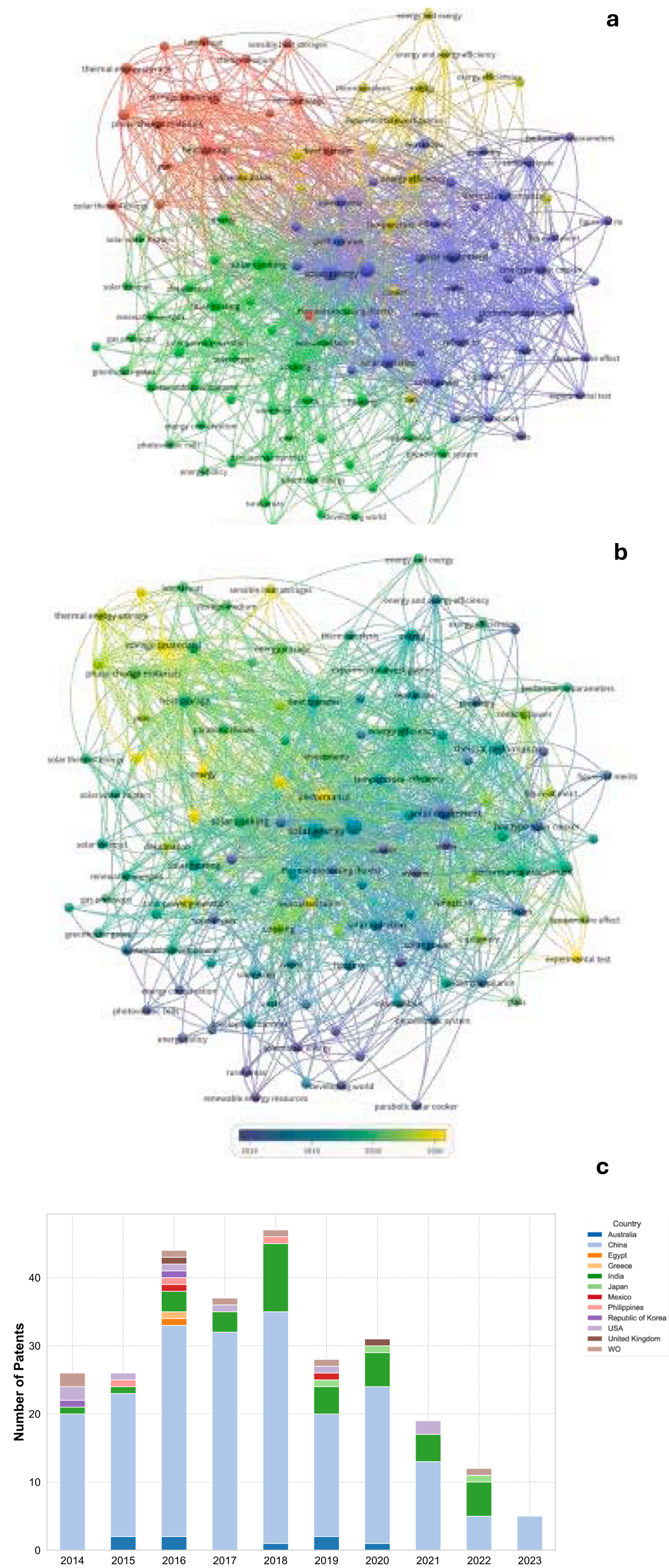

Fig. 3 a). Cluster distribution of the recently published information on solar cooking between 2014 and 2024, b) Time analysis of cluster distribution, and c) Number of patents registered at the WIPO platform.

It is evident that between 2014 and 2020, research trends have evolved significantly, reflecting a growing emphasis on sustainable development and technical innovations. The frequency of publications has steadily increased, highlighting a rising interest and advancements in renewable energy, energy efficiency, and sustainable development. There has been a noticeable shift towards integrating advanced technologies and materials, such as phase change materials (PCMs) for thermal energy storage and sophisticated solar cooking systems. This period also saw a growing number of experimental and modelling studies to optimise energy systems and enhance their performance under varying climatic conditions. These trends indicate a robust and dynamic research landscape addressing global energy challenges and promoting sustainable practices.

Analysis reveals significant trends and developments in this field using a database of patents related to solar cooking extracted from the patent Scope database [42] covering the period from 2014 to 2024. Over the past decade, patent activity for solar cookers and their components has significantly increased, reflecting a global commitment to renewable energy and sustainable living. Leading countries like India, the United States, and China have invested heavily in research and development. This trend highlights the growing awareness of the environmental and economic benefits of solar cooking and a response to the rising demand for alternative energy sources. Innovations in this period have focused on improving efficiency, usability, and design, making solar cookers more practical and accessible.

Notable patents include India's "Wall Mountable Solar Cooker" (201621012608), which addresses space limitations in urban areas, and the "Fresnel Lens Holding Rotatable Shaft 'Support Device" (201841035758), which enhances sunlight concentration for cooking. The patent "Solar Cooking Means Along Radial Plane of Sun" (201741039376) optimizes solar energy absorption by aligning cooking devices with the sun's radial plane. While China leads in patent filings due to substantial investments in renewable energy research, supportive government policies, and a strong manufacturing base, developed countries such as the United States focus more on qualitative innovation. With advanced research facilities, significant funding, and a strong culture of innovation, these nations drive technological advancements that enhance the efficiency and functionality of solar cookers. This contrast highlights how different strategies contribute to global progress in solar cooking technology. These nations focus on integrating cutting-edge technologies and materials to enhance solar cookers' efficiency and functionality, further contributing to global advancements in this field.

Developed countries' involvement highlights a global recognition of the importance of solar cooking technologies. This comprehensive review underscores the significant progress made and the ongoing dedication of the scientific community to advancing solar cooking technologies. As research expands and innovates, further developments can be expected, driven by the demand for sustainable and eco-friendly cooking solutions. This research showcases the technological advancements in solar cooking and highlights its potential to inspire behavioural changes toward sustainability.

4. Solar cooking: environmental, sustainability and global impact

Solar cookers can motivate behavioural changes toward circular economy and sustainability. They hold great potential for diverse applications such as cooking, drying, pasteurization, and sterilization [43, 44]. They operate by converting solar radiation into heat energy, concentrating sunlight, converting it into heat, and trapping that heat through isolation.

Despite having zero emissions and being fuel-free, solar cookers are not widely adopted in developed economies [43,45]. They find significant usage in developing countries, especially in Africa and South Asia, addressing the cooking needs of poor households with benefits like durability and improved nutritional value [46].

Solar cookers contribute positively to health and the environment, reducing household air pollution and its associated health risks. According to the World Health Organization (WHO), solar cookers can help eliminate household air pollution. In 2020, household air pollution was responsible for an estimated 3.2 million deaths, including over 237,000 deaths of children under the age of 5 in developing countries. Furthermore, the combined effects of ambient air pollution and household air pollution are associated with 6.7 million premature deaths annually worldwide [47]. A systematic review and meta-analysis reported that clean cooking technologies, including solar cookers, can reduce kitchen PM2.5 concentrations by up to 83 % and carbon monoxide levels by 82 %, significantly lowering exposure to air pollutants that cause pneumonia and chronic obstructive pulmonary disease (COPD) [48]. However, real-life implementation studies indicate that the effectiveness of solar ovens in reducing household air pollution depends on user adoption and behavioural patterns, as observed in a randomised controlled trial in Senegal, where limited usage restricted their impact on pollution exposure [49]. They can serve as alternatives to traditional cooking stoves during crisis periods, facilitating water pasteurization and medical instrument sterilization [44,50].

In the European Union, solar cookers offer a sustainable cooking solution aligned with goals to reduce greenhouse gas emissions and energy consumption. Despite EU efforts, households account for 21 % (740 Mt) of annual emissions [51], with 6 % coming from electrical appliances [52]. Solar cookers can help achieve the EU's 2030 objectives, targeting a 36 % reduction in emissions and a 29 % decrease in energy consumption from 2021 levels [53].

Recent advancements have enhanced the efficiency and user-friendliness of solar cookers, making them more appealing for both developed and developing countries. These improvements contribute to their broader acceptance [54–56].

Studies highlight the environmental benefits of long-lived solar cookers, indicating a substantial reduction in environmental impact by up to 65 %, including global warming potential [14,43]. By using reused materials, it also minimises environmental impact and costs [43].

To increase the global popularity of solar cooking, it is essential to present it as a viable solution for cooking-related challenges, emphasising its positive social and environmental impacts. Fig. 4 summarises the factors impacting solar cookers' popularity and the actual reality.

Adopting solar cooking can be beneficial at the household level and on a larger scale. However, successful implementation depends not only on technical factors such as price and design but also on health and environmental considerations, as well as customers' needs and various political and economic factors such as energy and cost savings and environmental policies. SCI has reported the number of known solar cookers worldwide to be over 4.02 million, avoiding 5.99 t of CO_2 emissions annually [57].

Understanding these barriers is crucial to devising strategies to facilitate the adoption of solar cooking technologies in developed nations, where the context and consumer behaviour differ significantly from those in developing countries.

Beyond economic and social considerations, solar cookers play a significant role in advancing several United Nations Sustainable Development Goals (SDGs) by promoting clean energy, environmental sustainability, and public health. They support SDG 7 (Affordable and Clean Energy) by reducing reliance on non-renewable fuels and fostering renewable alternatives while mitigating deforestation and carbon emissions, aligning with SDG 13 (Climate Action). Additionally, they lower indoor air pollution, improve respiratory health (SDG 3: Good Health and Well-being), and enhance food security by preserving nutritional quality and expanding access to clean cooking (SDG 2: Zero Hunger) [5,6]. These benefits position solar cooking as a key technology for a more sustainable and resilient global food system [5].

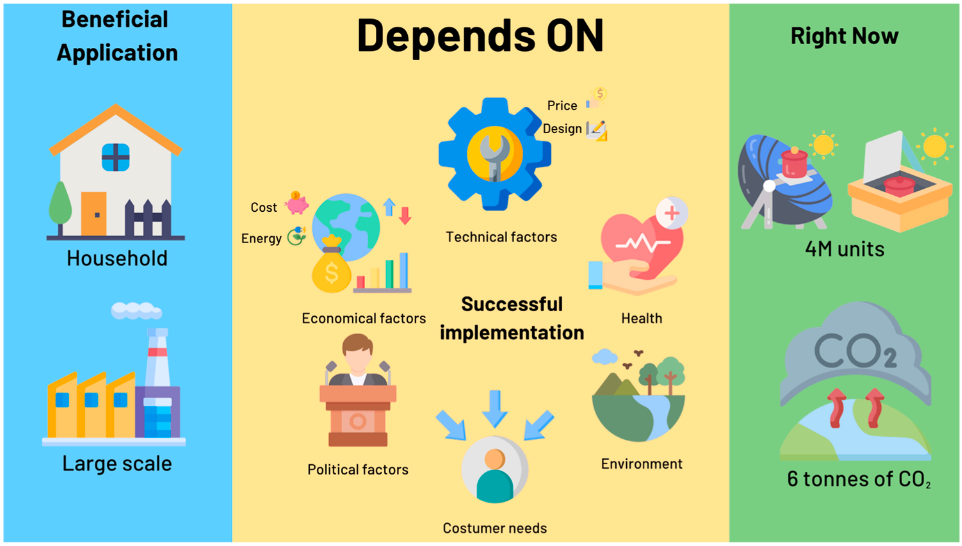

Fig. 4. Holistic impact: global deployment of solar cookers and emission reduction.

5. Challenges of solar cooking technology adoption in developed countries

The adoption of solar cookers in developing countries is influenced by economic, social, cultural, environmental, political, and technical factors. Addressing these variables is crucial for successful solar cooking projects, necessitating comprehensive needs assessments for target groups [58,59]. In developed countries, particularly in Europe, the adoption of solar cooking faces multifaceted challenges despite its potential benefits for households and larger-scale applications.

Solar cookers significantly reduce CO_2 emissions, which is crucial for addressing global warming and pollution. The combustion of propane and butane in liquefied petroleum gas (LPG) releases significant amounts of CO_2, contributing to air pollution and health hazards. Herez et al. [12] have quantified CO_2 emissions from various cooking environments, demonstrating that using solar cookers can lead to substantial reductions. Additionally, solar cooking helps reduce respiratory and eye diseases caused by indoor air pollution compared to traditional cooking methods.

Economic analyses based on primary studies demonstrate the financial viability of solar cookers. Mahavar et al. [60] evaluated a Solar Rice Cooker with a short payback period and high net present value (NPV), while Kumar et al. [61] showed significant fuel cost savings and a simple payback calculation for dual-purpose solar devices. Although solar cookers may require an initial investment, field studies confirm that operational costs are significantly reduced over time. For instance, Sosa et al. [62] observed substantial household savings in rural Mexico due to reduced firewood consumption. These findings confirm that solar cookers can significantly lower long-term energy expenditures and offer a sustainable alternative to conventional cooking methods.

Several studies have explored the life cycle assessment (LCA) and levelised cost of cooking a meal (LCCM) to quantify the long-term financial and environmental benefits of solar cookers. Field-based studies, such as Sosa et al. [62], highlighted how solar cooking reduces fuelwood extraction and CO_2 emissions, offering both environmental and economic gains. Although earlier reviews [26,43,63] have summarised these impacts, primary studies confirm that variations in design and material selection - with some models using low-cost recycled materials and others relying on high-performance components - critically influence overall sustainability. These assessments highlight the need for further optimisation to enhance durability and recyclability while maintaining affordability.

One significant barrier is the initial investment costs and perceived slow financial return, which may discourage potential users in developed economies [58,64]. Technological and practical limitations further complicate the adoption process. The performance of solar cookers is highly dependent on consistent sunshine, which is less reliable in certain European climates, particularly during winter. Integrating solar cooking into existing kitchen systems presents challenges, as many households need more space or infrastructure to accommodate these devices. Furthermore, while solar cookers can effectively prepare various meals, their efficiency drops for dishes requiring high temperatures or prolonged cooking times, which can be perceived as less practical than conventional methods [55,56,64].

Despite their numerous advantages, the adoption of solar cookers in developed countries remains limited due to economic and cultural barriers. Primary field evaluations show that while the long-term savings are significant, the initial investment cost and the perceived delay in financial return remain critical constraints, particularly where conventional energy sources are relatively cheap [43,61,62,65]. Economic feasibility studies, such as those by Misra et al. [63] and Gorjian et al. [26], highlight that while solar cookers can significantly reduce long-term energy expenses, the upfront cost and lack of financial incentives slow down their adoption. The levelized cost of cooking a meal (LCCM) and life cycle assessment (LCA) analysis further indicate that solar cookers are a cost-effective alternative in the long term [26,43,63]. Yet, these economic benefits are not always well-communicated to potential users.

Practical limitations, such as climate dependency and integration with existing kitchen infrastructure, remain key barriers [26]. Cultural preferences for conventional cooking methods, particularly those requiring direct flame or high-temperature frying, further limit the adoption of solar cookers. Studies have shown that in some regions, users perceive solar cookers as slow and incompatible with their culinary traditions, leading to resistance to transitioning away from conventional stoves [58,59].

Beyond cultural challenges, the lack of strong policy incentives and regulatory frameworks hinders widespread adoption. Unlike solar panels or electric vehicles, solar cookers receive minimal government subsidies and are rarely included in national energy policies, making them financially less attractive to consumers [56,64]. Furthermore, a lack of standardised certification and testing procedures reduces consumer confidence and market penetration, as emphasised in previous studies on the diffusion of solar cooking technologies [26,58,66]. Addressing these issues requires targeted awareness campaigns, governmental incentives, and the development of hybrid solar cookers that integrate auxiliary heating sources to improve usability in variable climates.

Non-governmental organisations (NGOs) are crucial in promoting solar cooker adoption, particularly in regions where access to clean cooking technologies is limited. Organisations such as Solar Cookers International and the Public-Private Alliance Foundation have led awareness campaigns, training initiatives, and large-scale distribution efforts. Gorjian et al. [26] provide a comprehensive analysis of over 350 NGOs actively working in this space, demonstrating their impact in reducing biomass dependency and mitigating the adverse health effects of indoor air pollution. Their efforts highlight the socio-economic benefits of solar cookers, particularly for marginalised communities.

Beyond environmental benefits, solar cooking supports economic empowerment through job creation and income generation. By reducing household fuel expenses, families - especially in low-income areas - can allocate resources toward essential needs such as education and healthcare. Additionally, solar cookers create opportunities for entrepreneurship, particularly in food preparation for local markets, enhancing economic self-sufficiency. Additionally, solar cookers create opportunities for entrepreneurship, particularly in food preparation for local markets, enhancing economic self-sufficiency [26,43]. Cost savings from reduced fuel use further support financial stability, making solar cooking a viable tool for economic resilience [63].

Expanding solar cooking programmes has created jobs in multiple sectors, including manufacturing solar cookers, distribution networks, training programmes, and maintenance services. Initiatives supported by NGOs such as Solar Cookers International have successfully facilitated employment opportunities, particularly for women, by integrating solar cooking into sustainable development projects [26]. Additionally, local economies benefit from the increased demand for solar cookers and related technologies, stimulating growth in renewable energy markets and reducing dependency on costly imported fuels.

Solar cooking technologies enhance long-term community resilience by reducing fuel dependency and improving food security. Households no longer relying on wood, charcoal, or LPG benefit from lower energy expenditures and more excellent stability amid supply chain disruptions [26,43]. These socio-economic advantages reinforce the potential of solar cooking as a sustainable, long-term alternative that extends beyond environmental benefits to tangible, measurable impacts on livelihoods and local economies [63].

Policy and regulatory frameworks in developed countries must provide more significant support for solar cooking technologies. Unlike other renewable energy technologies, solar cookers lack standardised testing, certification, and policy incentives, hindering their commercial viability. Studies stress the need for government-backed subsidies and stronger regulatory mechanisms to promote widespread adoption [26,58,66].

Ongoing innovation and research and development (R&D) are essential to improving solar cookers' efficiency, affordability, and usability, ensuring their viability as an alternative to conventional methods. Future efforts should prioritise the development of eco-design guidelines, life cycle management strategies, and integration hybrid cooking technologies to improve adaptability in diverse climates. Additionally, social life cycle assessment (LCA) studies are needed to complement the existing economic and environmental analyses [55,56,58]. Table 1 presents recent studies focused on the financial analysis of solar cookers, highlighting the key insights from various countries.

Beyond technological advancements, overcoming cultural, economic, and policy barriers remains critical for widespread adoption. While significant progress has been made in optimising the thermal performance of solar cookers, real-world implementation still faces challenges. Policymakers, researchers, and industry leaders must collaborate to bridge this gap, ensuring that innovations translate into practical solutions. Targeted awareness campaigns, regulatory incentives, and stronger policy frameworks can accelerate the adoption of solar cooking technologies in developing and developed regions.

Table 1
Economic analysis and key insights from recent solar cooking studies.

Authors	Countries	Key insights
[63]	India USA	Recent improvements in box-type solar cookers have enhanced efficiency and usability with new geometries, reflectors, and insulating materials. Economic analyses cover payback periods, net present value, benefit-cost ratios, internal rate of return, and levelized costs. Phase change materials show promise for late-evening cooking.
[26]	Iran India	Examines design, advancements, and economics of concentrating solar cookers (CSCs), emphasising their high-temperature capabilities and reduced cooking times for large-scale applications. It reviews parabolic trough, parabolic dish, and Fresnel lens solar cookers. Despite high initial costs, CSCs offer significant advantages.
[43]	United Kingdom Spain	Homemade solar cookers can significantly reduce greenhouse gas (GHG) emissions, waste, and electricity consumption. They can also enhance social well-being and promote sustainability behaviours.
[62]	Mexico	The study presents an economic analysis highlighting family cost savings and the benefits of reducing timber consumption. It found that using solar cookers led to a 50 % reduction in fuel wood consumption among participating families. This reduction results in less frequent and less intense fuel wood extraction, decreased CO_2 emissions, and better preservation of endangered tree species like Quercus and Pinus.
[60]	India	The paper details the modelling, fabrication, and field testing of a Solar Rice Cooker (SRC). It includes theoretical calculations to determine available solar power and evaluate system parameters. The SRC container's top surface reached a maximum temperature of 142 °C, successfully cooking rice in about 2 h. The study also provides an economic analysis of the Solar Rice Cooker (SRC), showing it is economically viable with a high net present value (NPV) and a short payback period.
[61]	India	The study presents a simple economic analysis demonstrating the financial viability of the solar device, with a payback period based on fuel savings. The design provided significant cost savings by replacing conventional fuel sources. Additionally, solar devices reduce dependency on traditional fuels and lower CO_2 emissions. It offers dual functionality as a cooker and hot water system, promoting sustainable energy use and environmental conservation with high efficiency.

6. Solar cooker's thermal performance and modelling

Evaluating a solar cooker's thermal performance often involves theoretical modelling and experimental procedures. Theoretical modelling comprises mathematical equations to simulate the behaviour of a solar cooker under various conditions, such as different design characteristics, materials, and climatic factors like wind speed, ambient temperature, and solar radiation intensity [67]. Mathematical models based on energy balance equations applied to each component of a solar cooker facilitate the analysis of heat exchange mechanisms by conduction, convection, and radiation. Modelling can be based on steady state or transient heat transfer, considering the dynamic nature of temperature changes inside the cooker over time [68,69].

Various methods have been used to improve the thermal performance of solar cookers. These include using sun-tracking mechanisms and lenses to increase radiation absorption during the day [70,71], optimising the geometry of absorber plates [61], and the number of cooking pots in the solar cooker [38].

Although the thermal performance of box-type solar cookers is commonly assessed using figures of merit F_1 and F_2, these parameters have limited applicability in high-temperature cookers or when additional optical enhancements are introduced [36,37].

Recent studies have proposed the Cooker Opto-Thermal Ratio (COR) as a more general and robust thermal performance parameter that allows for comparison across different cooker geometries and designs, including concentrating cookers [36,37]. COR integrates optical efficiency and thermal losses into a single indicator, offering improved comparability across technologies.

Depending on the weather conditions, some solar cookers chambers can reach 300 °C in as little as 20–30 min [72]. Reports indicate that even a simple commercial solar panel cooker can achieve relatively high temperatures. The cooking time for 2 kg of food can vary, typically taking 1–2 h to cook vegetables, rice, eggs, and fish and up to 3–4 h for foods like potatoes, root vegetables, beans, bread, and meat. Stews, soups, and roasts may take up to 5–8 h, depending on the amount of food and the type of pot used [73]. Any cooking pot can be used, but the characteristics to enhance its efficiency include dark colour, thin metal surfaces, a low height-to-diameter ratio, a 15 cm diameter, and a transparent concave lid with a hole [8,38,74]. To provide a comprehensive overview of recent theoretical and experimental studies on solar cookers' thermal performance and modelling, Table 2 summarises various researchers' objectives and types of studies.

Solar cookers work differently from standard ovens because they use different irradiation wavelengths. A transparent pot's lid allows visible, near-UV, and near-infrared wavelengths to pass through and cook the food [4,8]. As a result, the food is cooked with a substantial contribution of visible light.

Comparing efficiency is challenging due to varied test conditions such as weather conditions, wind speed, ambient temperature, and solar radiation intensity, which vary with seasons and location. This parameter is determined by the ratio between the amount of solar energy transferred to the test load and the pot and the amount of solar energy collected by the cooker. The parameter value typically ranges from 10 % to 30 % for water loads [4]. Normally, solar cookers can prepare two meals daily when solar radiation is intense from 10:00 a.m. to 2:00 pm [73]. Gathering key variables in real time over extended periods, encompassing diverse atmospheric conditions, and using different solar cookers significantly enhances our understanding of each cooker's operation. Compiling an extensive and detailed database facilitates the study of thermal performance and could serve as a robust foundation for conducting more profound analyses through machine learning techniques.

Experimental procedures serve to validate theoretical models and obtain real-world data. A set of commonly used performance parameters is required to analyse the performance of solar cookers made by different manufacturers with distinct designs and geometries. These test criteria are crucial for licensing purposes and ensuring the quality of solar cookers that are made available to users [101].

Testing procedures for solar cookers were developed based on international standards [27]. They comprise three primary testing standards for solar cookers commonly used in various parts of the world [45,66,102–104]. These primary testing standards differ significantly in scope, complexity, and results. The thermal performance of solar cookers is commonly assessed using standardised metrics such as the first and second figures of merit (F_1 and F_2) and standard cooking power. F_1 quantifies the ability of a cooker to reach high stagnation temperatures under no-load conditions, while F_2 evaluates its efficiency in transferring heat to the cooking vessel under loaded conditions [11]. Initially introduced by Mullick et al. [104] and refined by Funk [103], these parameters remain central to performance evaluation. Additionally, standard cooking power normalises the thermal output of different cooker designs under reference solar irradiance, enabling cross-comparisons [9]. Recent studies have refined these metrics to enhance their applicability across diverse solar cooking technologies and climatic conditions [105].

A generalised comparative analysis between the three established standards is summarised in Table 3.

The procedures followed to evaluate the performance of solar cookers consist of the determination of the following:1) Cooking time for different food products; 2) Time required for sensible heating of a known quantity of water up to the boiling point; 3) Stagnation plate temperature recorded in a test without load. The second and third methods are better approaches because the first method introduces uncertainties stemming from ingredient variations and relies on the observer's judgment to determine precisely when the food is fully cooked [9]. Modelling and experimental procedures complement each other, offering comprehensive insights into solar cooker performance and facilitating design optimisation and selection.

7. Integration of kinetic models and machine learning in solar cooking

Exposing food to heat treatments induces significant transformations in its chemical, physical, and sensory attributes. Understanding and effectively controlling the rate and nature of these changes is crucial for managing process operations and maintaining the desired overall food quality. Applying mathematical and algorithmic models for food quality parameters enhances understanding and prediction of phenomena, including the temporal degradation of nutritional quality [107].

Reaction kinetic studies play a crucial role in quantifying the rate of change for different food parameters, influenced by factors like time, temperature, pressure, moisture, acidity, ingredient quantities, and environmental conditions. Kinetic modelling quantifies the level of degradation in nutritional and sensory aspects and the activity of enzymes and microbes during food processing. Specific reactions lead to a loss of quality, while others contribute to the desired colour or flavour [107,108].

Researchers have utilised modelling techniques to optimise solar cookers thermal performance [29,68,85] and choose materials for improved energy efficiency and durability [3,7]. Despite these efforts, there remains to be more information regarding the kinetic modelling of changes in compounds and sensory properties of food cooked using solar energy. Such insights are crucial for understanding the potential quality and nutritional benefits of this cooking method for food.

Previous research has highlighted the significant influence of solar cooking on enhancing food quality [38,72]. However, until nowadays, only one published scientific work was found where solar cooking is compared with traditional food processing techniques, analysing the effect of direct solar cooking with and without UV filter vs. traditional methods on foods' polyphenolic antioxidants, vitamins, and carotenoids [72].

Human involvement in the food industry presents challenges in maintaining the demand-supply chain and ensuring food safety. To address these challenges, industrial automation, incorporating artificial intelligence (AI) - including machine learning (ML), emerges as a powerful solution. Implementing AI-based systems optimises food production and delivery by streamlining processes, reducing waste, and predicting maintenance needs, thus enhancing overall operational efficiency [109]. These systems can improve quality control, ensure consistency in product standards, and adapt to changing market demands with greater agility. Moreover, AI-driven analytics can provide valuable insights into consumer preferences and trends, enabling more accurate forecasting and inventory management, ultimately leading to increased profitability and sustainability in the food industry [110].

ML algorithms analyse patterns extracted from data, learning from labelled examples to make accurate predictions or decisions [111,112]. It is essential to find ways to extend the application of AI technologies and take more significant advantage of its emerging opportunities, which can lead to substantial developments in the whole food industry [110,113].

ML can become a powerful tool in predictive modelling, particularly in food processing, such as solar cooking. Analysing large datasets that store features such as temperature, radiation, wind, meal composition, and cooking time allows informed decision-making and the optimisation of processing parameters in real-time [111]. Constantly analysing sensor

Table 2
Theoretical and experimental thermal performance and modelling studies.

Reference	Type of Cooker	Type of Study	Objective of the Study	Main Conclusions
[75]	Various	Experimental	To measure the cooking efficiency of solar thermal cookers and enhance SCI's existing performance evaluation process (PEP).	Cooking efficiency: 18,9–35,2 % (varies by cooker type). SCI method improves accuracy.
[76]	Parabolic	Experimental	To determine the performance of a basket-based solar cooker in terms of cooking potential, power, and energy efficiency in Uganda.	Suitable for cooking most Ugandan foods (>238 days/year), except beans, due to high energy demand. Reduces fuel use, health risks, and wood collection burden.
[77]	Parabolic	Experimental	To determine the exact concentration ratio (CR) for a parabolic solar concentrator using thermographic imaging.	CR ranges from 20 to 151. Peak energy efficiency: 25 % (mean: 15,3 %). Curvature irregularities reduce uniformity and efficiency
[78]	Box	Theoretical and Experimental	To enhance the thermal performance of a solar box cooker using nanocomposite materials.	Nanocomposite coating improves thermal efficiency (56,21 - 31,77 % vs. 33,90 - 24,90 % without coating). Max bar plate temperature: 163,74 °C vs. 113,34 °C. Cooking time reduced (30 - 58 min vs. 51 - 110 min for conventional cookers)
[30],	Parabolic	Experimental	To evaluate and compare the performance of two similar storage cooking pots during solar and off-sunshine cooking periods.	Sunflower oil pot enables faster cooking and higher maximum temperatures under sunlight. Erythritol PCM pot retains heat better, reducing temperature drop and improving heat utilization efficiency.
[79]	Box	Theoretical and Experimental	To construct and carry out a performance evaluation of the solar box cooker.	Functional solar box cooker with stagnation temperature of 104 °C. It performs well under high solar intensity and is suitable for regions with intense solar radiation.
[21]	Parabolic	Experimental	To ensure the completion of the cooking process under sudden reduction in solar irradiance by determining heat retention time.	Heat retention time and Cooker Opto-Thermal Ratio (COR) ensure cooking completion under varying solar irradiance. SBC: COR = 0138; SPD-SCC: COR = 0241
[29]	Parabolic	Experimental	To design and construct a functional parabolic solar cooker as an alternative renewable energy source and evaluate its energy and exergy performance.	The parabolic cooker is built with local materials, with an average energy efficiency of 39 % and an exergy efficiency of 44 %. Reaches temperatures suitable for cooking and crop drying.
[7]	Box	Theoretical and Experimental	To present a novel twin-chamber community solar cooker design to replace biomass-based cooking and evaluate its performance.	Twin-chamber cooker (TCCS) has a larger aperture and volume, reducing heat loss and improving efficiency. Payback period: 25 - 72 months (varies by fuel replaced). Significant CO_2 emission reduction.
[80]	Parabolic	Experimental	To compare the performance of parabolic solar cookers using different reflective materials.	Mylar tape has the highest reflectivity and achieves the highest temperature. Aluminium foil and stainless steel result in lower maximum temperatures.
[11]	Box	Theoretical and Experimental	To propose revising the existing procedures for testing and performance comparison methods for solar box cookers, aiming to develop a more precise standard.	Revised figures of merit improve solar box cooker characterization, enhancing accuracy in performance evaluation. Supports future standard development.
[81]	Box and Parabolic	Experimental	To examine mathematical modelling and experimental validation of two types of solar cookers: box and parabolic.	The parabolic cooker achieved higher temperature gain. Box cooker suitable for 8 – 8,4 kWh/m² irradiation. Theoretical and experimental results show strong consistency.
[28]	Parabolic	Theoretical and experimental	To evaluate the thermal efficiency of a paraboloid concentrator solar cooker in Algerian climatic conditions using an optical simulation approach.	Paraboloid solar cooker reaches cooking temperatures in clear sky conditions across Algeria; performance drops under overcast skies—temperature maps aid efficiency prediction.
[82]	Scheffler reflector	Experimental	To perform energy and exergy-based thermal analysis of an innovative solar bakery unit powered by Scheffler reflector.	Solar bakery powered by Scheffler reflector achieved 25–75 % energy efficiency and 6,62 - 56,46 % exergy efficiency. The baking chamber maintained ~180 °C with uniform temperature distribution
[19]	Parabolic	Theoretical and Experimental	To present different optimization considerations in designing a parabolic solar cooker and analyse thermal and optical losses.	The parabolic cooker has higher efficiency and heating capacity than box-type cookers. Optimization reduces thermal and optical losses.
[83]	Parabolic	Theoretical and Experimental	Develop a dynamic thermodynamic model of a parabolic solar cooking system with heat storage and compare the model solution with experimental measurements.	A 50 W/m² increase in solar radiation raises heat storage temperature by ~4 °C. A 5 % increase in reflectance or absorptance improves heat storage by 3,6–3,9 °C. The model matches experimental data.
[84]	Box	Theoretical	To model the efficiency equation of a solar cooker to provide a mathematical framework that engineers can use to design more efficient solar cookers.	Developed an efficiency equation for solar box cookers to estimate performance and guide design improvements.
[85]	Box	Experimental	To analyse the thermal performance of a box-type solar cooker using experimentally obtained F_2 data for different loads of water and to validate the proposed methodology.	Fins and paraffin wax improve heat transfer and reduce cooking time. The proposed test procedure accurately predicts thermal performance.
[86]	Box	Theoretical and Experimental	To test and model the performance of a box-type solar cooker over an extended period and to validate the model with experimental data.	Model validation showed $a < 4$ % error over one month. Results indicate a high potential for solar cooking in developing countries
[18]	Box	Theoretical	To develop and validate a mathematical model for a box-type solar cooker with internal reflectors.	The model accurately predicts thermal behaviour. Temperature increases with more internal reflectors, peaking at five steps.
[87]	Box	Theoretical and Experimental	To compare the performance of box solar cookers with and without internal reflectors using theoretical modelling and experimental testing.	Cookers with internal reflectors achieved higher stagnation temperature and cooking power. Reflector design significantly improved efficiency.
[88]	Box	Theoretical	Design and development of the solar oven.	A solar oven model was developed using the CBS Finite Element Method. Results show good agreement with experimental data.

(*continued on next page*)

Table 2 (*continued*)

Reference	Type of Cooker	Type of Study	Objective of the Study	Main Conclusions
[89]	Parabolic	Theoretical and Experimental	To obtain a mathematical thermal model to explain the behaviour of the solar cooker "Jorhejpataranskua" and compare numerical results with field tests.	Model validation showed $a < 4$ % error—standardized cooking power: 111,6 W (aluminium pot), 102,4 W (stainless steel pot).
[90]	Parabolic	Experimental	To present two charging experiments of solar heat storage coupled with a solar parabolic trough for cooking purposes and evaluate the performance with and without insulation.	The insulated absorber reaches temperatures >200 °C for efficient cooking. An uninsulated absorber is better at low temperatures, and insulation is essential at higher temperatures.
[67]	Parabolic	Experimental	To define and evaluate an innovative layout of a portable solar cooker of the standard concentrating parabolic type that incorporates a daily thermal storage utensil.	Cooking for a family is possible with heat storage. The insulated box allows for cooking dinner and breakfast storing heat all day.
[60]	Box	Theoretical and Experimental	To model, fabricate, and test a Solar Rice Cooker (SRC) under different conditions to evaluate its performance and economic viability.	Solar rice cooker cooks 0,4 kg rice in 2 - 2,5 h. The payback period and high NPV indicate suitability for rice cooking.
[65]	Box	Theoretical and Experimental	To present the design development, thermal, and cooking performance studies of a novel solar cooker named Single Family Solar Cooker (SFSC).	SFSC is small, lightweight, and inexpensive. Good thermal and cooking performance year-round, ideal for middle-income families in developing countries.
[68]	Parabolic	Theoretical	To introduce a novel solar cooker design and develop a mathematical model of the heat transfer processes involved.	Solar cooker with new design achieves high thermal performance with 144 °C stagnation temperature. Efficient insulation and polymeric glaze contribute to good year-round performance.
[91]	Box	Theoretical and Experimental	To design and simulate a solar cooker with mirror reflectors for two tracking modes and analyse the performance by simulating collected energy on the absorber.	Mirror reflectors improve energy collection, enhancing cooker performance year-round, particularly in winter.
[92]	Box	Theoretical and Experimental	To develop and apply a mathematical model of the heat transfer processes in a box-type solar cooker and validate it with experimental results.	The mathematical model shows good agreement with experiments. The model is applicable to studying any box-type solar cooker.
[70]	Fresnel lens concentrator	Experimental	To design a novel solar cooking stove using a Fresnel lens for high safety and efficiency in solar cooking and heating.	Fresnel lens solar cooker achieves high temperatures and energy efficiency, with the potential for indoor heating with solar tracking.
[93],	Box	Theoretical and Experimental	To develop a mathematical model that describes and simulates the thermal behaviour of a solar stove based on an electric resistance analogy.	The thermal model predicts solar stove behaviour in good agreement with experimental data. Recommended for solar stove design.
[94]	Box	Experimental	To design, fabricate, and test a multipurpose solar device for cooking and water heating that does not require sun tracking.	Solar cookers meet BIS standards for F_1 and F_2, efficiently cook and heat water, and are economically viable for low-income consumers.
[95]	Parabolic	Experimental	Propose solutions to perform cooking in the kitchen independent of the time of day or insolation, interactively, and with reduced conventional energy use.	Optimized energy transport enables cooking independent of time of day or solar conditions, reducing conventional energy use.
[94]	Box	Experimental	To design, fabricate, and test a truncated pyramid-type solar cooker/dryer that does not require tracking the sun.	The truncated pyramid solar cooker reaches 140 °C stagnation and 98,6 °C water temperatures. It meets BIS standards and is practical for cooking and drying.
[96]	Box	Theoretical and Experimental	To compare the performance of a cooking vessel with a depressed lid on lugs with that of a conventional vessel on lugs using a mathematical model and experiments.	Depressed lid vessel achieves a higher thermic fluid temperature of 8,4 % better performance than conventional cylindrical vessels.
[32]	Various	Experimental	To conduct a comprehensive study involving theoretical review, development work, experimental testing, and evaluation of various types of solar cookers.	Reflector cookers with glass mirrors achieve the highest temperatures; box and panel cookers perform better under cloudy conditions.
[97]	Box	Theoretical and Experimental	To develop a mathematical model to understand the heat flow process to the cooking vessel and compare the performance of a cooking vessel with a central cylindrical cavity with that of a conventional cylindrical cooking vessel.	Central cylindrical cavity vessel on lugs improves performance by 5,9 % compared to conventional vessels, 2,4 % more than floor-based vessels.
[9]	Box	Experimental	To experimentally investigate the thermal performance of a box-type solar cooker.	The box-type cooker can be used twice daily with maximum load for best performance. Meets international standards.
[98]	Box	Experimental	To propose a simple test procedure to determine design parameters for predicting the thermal performance of a box-type solar cooker.	The test procedure successfully predicts heating curves with close experimental agreement. Optical efficiency and heat capacity are critical.
[99]	Parabolic	Theoretical and Experimental	To improve the efficiency and functionality of solar cookers for communal dining centres catering to large quantities of food.	Improved cookers efficiently heat large pots, generate steam, and bake, which is ideal for communal dining centres.
[100]	Box	Theoretical	To show a mathematical model of a solar box cooker with a multi-step inner reflector and analyse numerical results for two applications.	The multi-step inner reflector cooker model matches experimental results. Helpful in evaluating and designing solar box cookers.

data and using feedback loops will enable algorithms to adapt the variables. This maximises efficiency and minimises resource wastage.

Recent studies have already demonstrated the practical applications of ML in solar cooking. Predictive modelling techniques have been employed to estimate cooking times and energy efficiency based on real-time meteorological data [114,115]. Additionally, integrating ML with automated sun-tracking systems has shown the potential to enhance usability and performance by dynamically adjusting to solar radiation levels [116]. Furthermore, studies have explored ML-based optimisation of redundant solar energy for cooking applications and the development of AI-driven models to improve solar cookstove performance predictions and comparative assessments of machine learning models for solar cooking [114,115,117]. These advancements bridge the gap between AI-driven models and real-world solar cooking applications, optimising energy use and improving food quality.

There needs to be more understanding and applying ML to solar cooking, particularly in automating systems. Although there is recognition of the benefits of automating solar ovens through sensors [70], integrating ML can further refine and optimise this process. Combining ML with an automatic sun-tracking system could enable the solar stove

Table 3
Different testing standards for solar cookers.

Testing Standards for Solar Cookers	Objective	Advantages	Limitations
American Society of Agricultural Engineers Standard ASAE S580.1 [45,66,103]	Compare the thermal performance of different solar cookers with different geometries under various environmental variables.	- At this moment, it is the only standard universal test. - Solar cookers are clearly distinguished by their different designs. - Estimates of solar cooker performance for different locations and dates.	- It does not address qualitative factors, e.g., ease of use, safety, or financial issues.
Bureau of Indian Standards Testing Method [104]	Evaluate the performance and efficiency of solar cookers.	- The information is presented in a more technical manner than the one provided in ASAE S580.1 - Relatively independent of the climatic variables	- It may be difficult to replicate in less developed areas. It is more complex and less universal. - It does not address qualitative factors, e.g., ease of use, safety, or financial issues.
European Committee on Solar Cooking Research Testing Standard [106]	Extensive performance evaluation and various qualitative factors, such as simplicity of use and safety.	- Useful for comparison of any cookers. - A significant portion of the test is allocated to attention to safety issues, ease of access to the cooking pot, estimated shelf life, and other more subjective but valuable values.	- It may be difficult to replicate in less developed areas. - It relies on measurements of the time taken for certain conditions to occur. - It is not well suited to multiple testing and requires a long time.

to operate smoothly without constant supervision, offering a significant advancement that may drive the widespread adoption of this technology in both industrial and domestic settings.

Embracing ML into solar cooking modelling is a significant step forward, offering a future with more sustainability, efficiency, and improved consumer satisfaction.

8. Research gaps and future perspectives in solar cooking

The current research on solar cooking highlights significant knowledge gaps that need attention. There needs to be more understanding of how solar cooking impacts food processing and quality and the need for tools to predict solar cooking performance.

To address these knowledge gaps and promote a deeper understanding of solar cooking, several key research areas and future directions can be identified:

- **Interdisciplinary collaboration:** Despite the potential benefits of collaboration across different disciplines, few comprehensive studies combine knowledge from multiple fields to address the complex issues related to solar cooking. Research on solar cooking is inherently interdisciplinary, requiring cooperation among various fields such as computer and information sciences, food engineering, food technology, food science, and nutrition.
- **Integration of thermal performance and degradation kinetics:** Combining thermal performance studies with degradation kinetics modelling can provide a comprehensive understanding of the potential impacts of solar cooking on food quality. This approach allows for a detailed analysis of how solar cooking affects the nutritional characteristics of food, revealing both positive and negative effects. By evaluating thermal efficiency and quality outcomes, researchers can better assess the overall benefits and drawbacks of solar cooking compared to traditional methods, thereby supporting more informed decisions about adopting and optimising solar cooking technologies.
- **Development of predictive models:** More prediction models must be created that accurately forecast food behaviour regarding temperature and quality during solar cooking. Developing a dynamic simulator for solar cooking that considers heat transport phenomena such as radiation, conduction, and convection, as well as the kinetics of food quality change, could significantly improve the accuracy of these predictions [69,81]. By including kinetic data for quality parameters and integrating it into the heat transfer simulator, a comprehensive quality simulator for solar-cooked products could be created. This could be incorporated into applications that predict product quality based on location, time, and weather forecasts [18,19].
- **Comparative studies with conventional cooking methods:** Adequate comparative studies can help determine if solar cooking can produce more nutritious and healthier meals. Kinetic modelling is essential for understanding a particular technology's nutritional and quality advantages. Though research on solar cooking is limited, extensive studies on other cooking methods can offer insights that may apply to solar cooking, potentially speeding up the development of new prediction tools [118].
- **Application of machine learning (ML) techniques:** Integrating kinetic models with ML techniques offers significant potential for enhancing solar cooking processes' precision, efficiency, and effectiveness. Understanding the potential nutritional benefits of solar cooking can also drive consumer adoption. The thermal cooking process can enhance nutrient digestibility, improve protein quality, texture, and appearance of products, and increase nutrient absorption.

Previous research has provided valuable insights into solar cooking, but many questions still need to be answered. Focused studies to fill these gaps can enhance our understanding of solar cooking and promote its adoption as a sustainable and green cooking method. Furthermore, bridging these knowledge gaps holds promise for accelerating efforts to reduce greenhouse gas emissions, mitigate global warming, and prevent deforestation by encouraging using renewable energy sources in domestic cooking.

9. Conclusions

Solar cooking offers a promising solution for sustainable and environmentally friendly cooking, particularly as non-renewable energy sources diminish and environmental concerns grow. However, significant gaps in our knowledge need to be addressed to realise the full potential of solar cooking. These include understanding the impact of solar cooking on food processing and quality, creating reliable prediction models for solar cooker performance, and conducting multidisciplinary research to tackle the complex issues associated with solar cooking. By addressing these challenges, future research can improve our understanding and adoption of solar cooking technologies, reducing greenhouse gas emissions, mitigating global warming, and preventing deforestation. This review emphasises the importance of ongoing innovation and development in solar cooking, highlighting the need for eco-design guidelines, life cycle management strategies, and comprehensive sustainability assessments. Integrating advanced modelling techniques, such as computational thermal simulations and artificial intelligence-based optimisation, plays a critical role in enhancing the efficiency and usability of solar cookers. While this review synthesises technical methodologies and performance indicators from the literature, its primary goal is to identify emerging trends and research needs across disciplines. Future studies should explore practical implementations of these technologies to optimise design and performance. Closing these knowledge gaps is crucial for promoting solar cooking as a viable alternative to conventional cooking methods, leading to a more sustainable and healthier future.

CRediT authorship contribution statement

Ana C. Araújo: Writing – original draft, Conceptualization. **Ana Gomes:** Writing – review & editing. **Pedro M. Rodrigues:** Writing – review & editing. **Cristina L.M. Silva:** Writing – review & editing, Conceptualization.

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.

Acknowledgements

This work was supported by National Funds from FCT - Fundação para a Ciência e a Tecnologia through project UIDB/50016/2020. The authors gratefully acknowledge this funding. Financial support for author Ana C. Araújo was provided by FCT through fellowship 2022.11249.BD.

Data availability

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

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