Sustainable Energy Research

REVIEW

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A systematic review and bibliometric analysis of electric cooking: evolution, emerging trends, and future research directions for sustainable development

Flavio Odoi-Yorke[1*]

Abstract

Many developing countries, particularly in Africa and Asia, still widely use traditional cooking methods that rely on solid fuels such as wood and charcoal. These inefficient and polluting cooking practices have severe health impacts due to household air pollution, and they contribute to environmental degradation through deforestation and black carbon emissions. This has driven growing interest in cleaner and more sustainable cooking alternatives such as electric cooking (e-cooking), improved biomass cookstoves, biogas systems, and modern fuel stoves that can reduce emissions and fuel consumption while providing a safer cooking experience. E-cooking has emerged as a promising option to traditional cooking methods due to sustainability, health benefits, energy efficiency, convenience, safety, and potential for grid integration, making it a promising alternative to traditional cooking methods. This study followed the PRISMA guidelines for systematic reviews to assess the existing literature on e-cooking from 1993 to 2023. In addition, the biblioshiny package in R software was used to perform bibliometric analysis to identify key trends and evolutions. The results indicate that the United Kingdom, the United States, Japan, Australia, and China are the top five countries leading in e-cooking research. The study identified promising areas for future research, such as optimising solar e-cookers using artificial intelligence techniques, integrating internet of things and automation technologies in e-cookers, integrating e-cooking appliances into smart grid systems, examining effective behavioural change interventions, and exploring innovative business models. The study findings highlight the need for interdisciplinary collaboration among researchers, engineers, social scientists, and policymakers to address the technical, economic, socio-cultural, and environmental factors influencing the transition to e-cooking.

Keywords Electric cooking, E-cooking, Clean cooking, Electricity, Sustainable development, Renewable energy, Bibliometric analysis, PRISMA

Introduction

Access to affordable, reliable, sustainable, and modern energy is crucial for achieving many of the United Nations' Sustainable Development Goals (SDGs) (Casati et al., 2023; D. Li et al., 2023; Pan et al., 2023). Energy poverty remains a harsh reality for millions worldwide, with around 733 million people lacking access to electricity and nearly 2.4 billion relying on inefficient and polluting cooking fuels and technologies, according to 2021 estimates (The World Bank, 2022).

The situation is particularly dire in sub-Saharan Africa (Robin & Ehimen, 2024), where over 568 million people lack access to electricity and nearly 923 million lack access to clean cooking fuels and technologies (IEA,

*Correspondence:
Flavio Odoi-Yorke
flavio.odoi-yorke@cctu.edu.gh
[1] Department of Renewable Energy Technology, School of Engineering, Cape Coast Technical University, Cape Coast, Ghana

2023). Only a small minority of African nations have established goals to provide universal access to electricity for their populations by the year 2030. While an additional 45% of African countries have also set targets for increasing electricity access, these targets fall short of the more ambitious objectives outlined under the United Nations' SDG 7 (IEA, 2023).

The use of solid fuels such as charcoal, firewood, dung, and coal for cooking remains widespread, particularly in developing regions (Aemro et al., 2021; Benti et al., 2021; Odoi-Yorke et al., 2022). While affordable, these traditional cooking methods have severe environmental and health consequences (Qiu et al., 2023). Inefficient combustion produces high levels of household air pollution with fine particulate matter, carbon monoxide, and other toxic pollutants (Ajieh et al., 2023; M. U. Ali et al., 2021a, 2021b; Anwar et al., 2021). According to the WHO (2023), household air pollution accounted for 3.2 million premature deaths globally in 2020, including over 237,000 children under 5 years. However, combining household air and outdoor air pollution contributes to 6.7 million premature deaths annually (WHO, 2023). Women and children bear a disproportionate burden as they tend to have higher exposure levels from household chores involving cooking and fuel collection (Geddafa et al., 2023).

Several cooking methods and fuels are used worldwide, including liquefied petroleum gas (LPG), biogas, and improved biomass cookstoves. LPG is a popular fuel for cooking, particularly in urban areas, as it is relatively clean-burning and efficient (Shupler et al., 2021). Nonetheless, it is a non-renewable fossil fuel, and its availability and affordability can be challenging in certain regions (Sidi Habib & Torii, 2024). Biogas, produced from the anaerobic digestion of organic matter, is a renewable and clean-burning fuel. However, its adoption has been limited due to the need for appropriate infrastructure and feedstock availability (Muvhiiwa et al., 2017). Improved biomass cookstoves, which are designed to burn solid fuels such as wood or charcoal more efficiently and with reduced emissions, have been promoted as a cleaner alternative to traditional cookstoves (Manoj Kumar et al., 2013; Mehetre et al., 2017). Nevertheless, solid fuel harvesting contributes to outdoor air pollution, deforestation, forest degradation, and climate change (Jagger & Kittner, 2017). In addition, the energy-inefficient burning of biomass releases black carbon, methane, and carbon dioxide, which are critical drivers of global warming (Lohri et al., 2016). Unsustainable firewood and charcoal production degrade forest ecosystems, diminish biodiversity, and exacerbate soil erosion. Therefore, transitioning to clean, modern cooking fuels and technologies is critical to protecting human health, mitigating climate impacts, and promoting environmental sustainability, especially in resource-constrained regions disproportionately reliant on solid fuels.

Electric cooking (e-cooking) can potentially improve the quality of life for people who cook using biomass by improving health, eradicating harmful emissions, and removing the need to collect fuelwood, thus freeing up time for other activities (Clements et al., 2020; Gelchu et al., 2023). E-cooking, through technologies such as hotplates, electric pressure cookers, rice cookers, and induction stoves, presents a promising solution to addressing indoor and outdoor air pollution (Kashyap et al., 2023). When coupled with renewable energy sources like solar photovoltaics, e-cooking can provide clean, sustainable alternatives to traditional biomass and fossil fuel-based cooking methods that cause indoor air pollution and drive deforestation.

Several review papers on clean cooking exist in the literature. However, review papers related directly to e-cooking are limited. In view of this, some of the review papers related to e-cooking are presented. For example, Kashyap et al., (2023) comprehensively reviewed clean and energy-efficient cooking technologies, focussing on solar, electric, and hybrid cookstoves. In addition, Lukuyu and Taneja (2023) explored the potential of promoting e-cooking technologies to stimulate electricity demand in Sub-Saharan Africa. Likewise, Kizilcec et al., (2022) thoroughly reviewed factors influencing the adoption and obstacles to the uptake of LPG, solar home systems, and e-cooking in Sub-Saharan Africa. Similarly, Leary et al., (2021) reviewed the challenges and opportunities in the emerging field of e-cooking from a consumer perspective. Yangka and Diesendorf (2016) quantified the advantages of scaling up e-cooking within the residential sector of Bhutan. Brown et al., (2017) reviewed obstacles that could impede the expansion of battery-powered e-cooking technology. Another study by Brown and Leary (2015) reviewed the behavioural change challenges of the e-cooking concept.

Afrane et al., (2022) applied bibliometric analysis to synthesise global research on clean cooking from 1990 to 2020. The authors revealed that LPG, biogas, and electricity are the three clean cooking fuels studied the most across various regions. Aramesh et al., (2019) comprehensively reviewed the advancements in solar cooking technology, highlighting various designs and their performance. The study recommended that, to advance solar cooker technologies, additional research and experimentation are required to identify the most effective configuration that is both cost-effective and socially acceptable. Gill-Wiehl et al., (2021) analysed the literature on affordability as a barrier to the adoption and consistent use of clean cooking stoves and fuels. They found that affordability metrics for clean cooking need to be rethought to account for the uncertain and irregular income streams of low-income households, the persistence of fuel stacking, and essential non-discretionary expenses such as food and water. Wright et al., (2020) examined the current technologies and systems for cooking food, particularly within low-income communities.

The studies above indicate limited research summarising the trends, advancements, and future outlook of e-cooking for sustainable development. This paper aims to bridge this gap by conducting a comprehensive systematic review combined with a bibliometric analysis to identify critical patterns and themes and uncover potential research directions in this growing field. The novelty of this study lies in its rigorous mixed-methods approach, combining bibliometric analysis to reveal performance metrics, collaborative patterns, trending topics, and intellectual clusters with a systematic review to qualitatively synthesise findings on the status, challenges, opportunities, and pathways for upscaling e-cooking. To the best of the author's knowledge, such an all-encompassing inquiry into e-cooking in the context of sustainable development does not exist. The study's main objectives are to (1) evaluate global research productivity and geographic contributions, (2) detect conceptual, intellectual, and social structures underlying the literature body, (3) synthesise technological progress, and (4) identify critical knowledge gaps to guide future research. The author believes that study findings can inform policy, investment, and programmatic priorities to harness e-cooking as an enabler of affordable, reliable, and sustainable energy for all. Importantly, this study will provide a comprehensive knowledge base to guide researchers in understanding critical gaps and opportunities for future investigation in this emerging domain.

Research methodology

Figure 1 displays the flowchart of the study approach adopted. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework was followed to select papers for this review. The PRISMA framework ensures a systematic and reproducible approach to literature identification, screening, eligibility assessment, and data extraction (Odoi-Yorke et al., 2023; Page et al., 2021; Sohrabi et al., 2021). The systematic literature search from the Scopus database focussed on papers on e-cooking published from 1993 to 2023 to address the research objectives. The study employed pertinent search term combinations, including {electric cooking} OR {e-cooking} OR {electric cooker} OR {e-cooker} OR {electric-cook} OR {e-cook} to filter the Scopus database. This study selected the Scopus database over alternatives such as Web of Science and PubMed because it contained many pertinent publications related to the research topic. As a broad abstracting and indexing database spanning numerous disciplines, Scopus offers accessibility to many international journals, ensuring comprehensive global coverage of research findings from

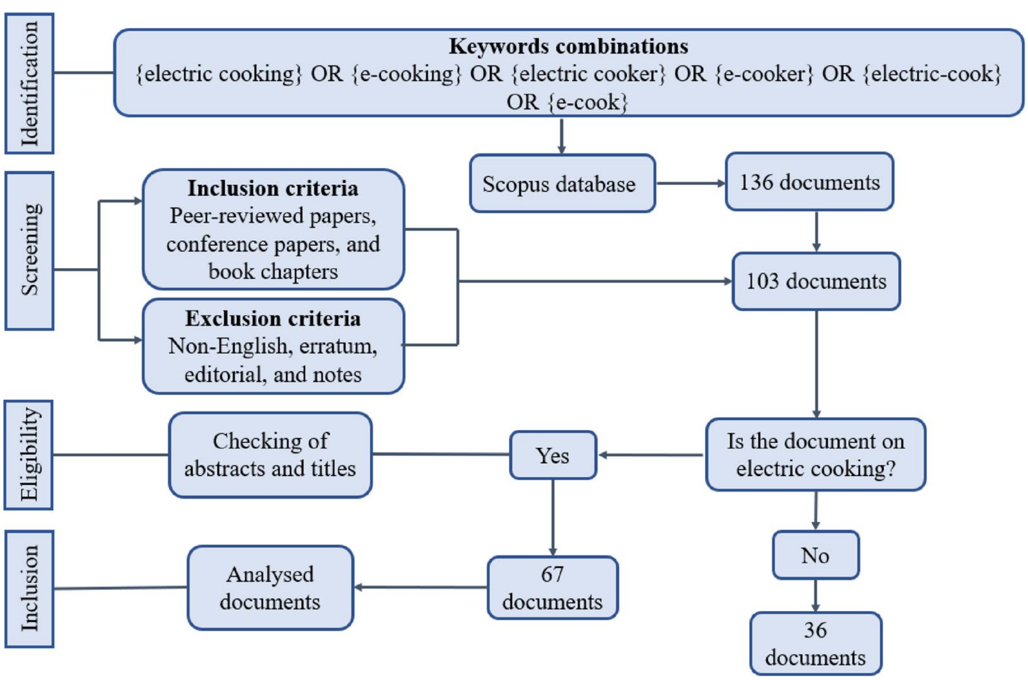

Fig. 1 The flowchart for the PRISMA approach

diverse geographical areas. Moreover, papers in the Web of Science are indexed in Scopus.

As seen in Fig. 1, the initial search, which yielded 136 documents, was screened based on predefined inclusion (peer-reviewed articles, book chapters, and conference papers) and exclusion (non-English papers, erratum, Editorial, and notes) criteria to obtain 103 documents (which comprise articles (65), book chapters (1), conference papers (31), and reviews (6)). Afterwards, information on journals, publication dates, author institutions, countries, sources, abstracts, citations, keywords, and bibliographies were downloaded in a CSV file on March 11, 2024, to perform analysis. After reviewing abstracts and titles, 67 documents were identified as relevant to e-cooking for this review. The eligible studies' full-text documents were systematically examined to identify emerging trends, advancements, and future research directions. This was done by reviewing each study to document research objectives, methodologies, key findings, and recommendations. It is worth mentioning that two independent researchers volunteered in the literature screening and data extraction stages to ensure the quality and reliability of the review process. Any disagreements or discrepancies were resolved through discussion and consensus. In addition, the risk of bias in individual studies was assessed using appropriate tools or checklists.

The study further performed bibliometric analysis using the biblioshiny package in R software, to provide insights into various aspects of the literature, such as publication trends over time, thematic map, and factorial analysis. Bibliometric analysis is a powerful tool for quantitatively evaluating scientific literature (Agyekum et al., 2024; Janik et al., 2020; Odoi-Yorke et al., 2024). These analyses could also help identify research hotspots, emerging themes, and potential knowledge gaps in the field of e-cooking.

Results and discussion

This section presents and discusses the significance of the results. It discusses articles published annually, thematic maps, factorial analyses, and findings from papers reviewed.

Analysis of articles published annually and top publishing countries

Figure 2 displays the number of articles published annually from 1993 to 2023. It can be observed that the number of articles published has shown an increasing trend over the years, with a more significant rise in recent years. As seen during the early years (1993–2009), the number of articles published was relatively low, with some years having no publications. This could indicate that e-cooking was not a major research area during that time or that the technology was still in its early stages of development. It can be seen that there has been a recent surge in articles produced from 2020 to 2023. The most notable observation is the substantial increase in articles published from 2020 onwards, with a peak of 23 articles in 2021. This publication surge could be attributed to the development of innovative technologies and

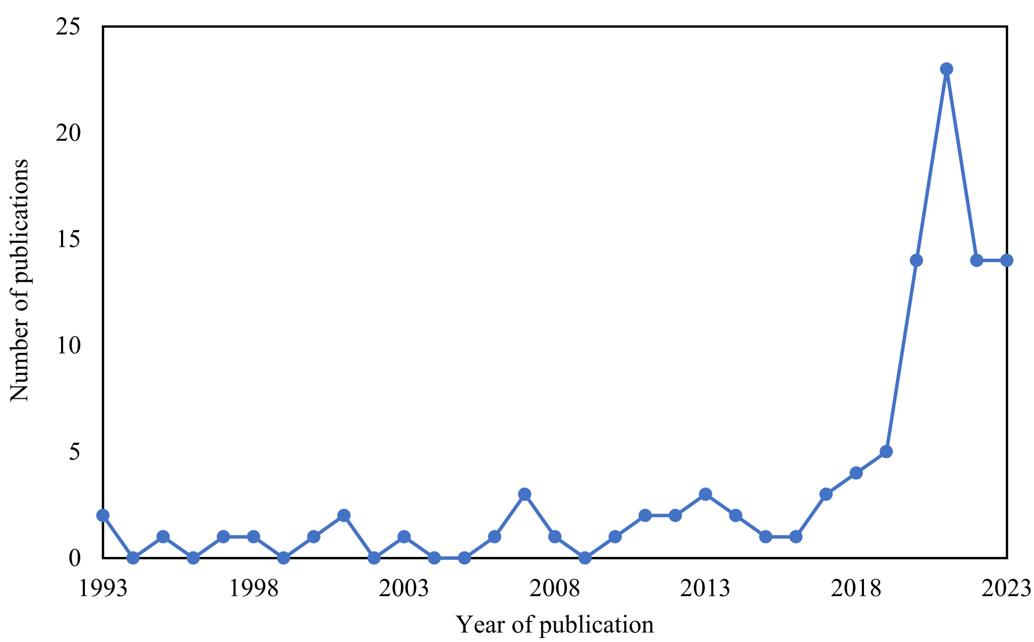

Fig. 2 Total articles published per year

the growing emphasis on environmental regulations and policies promoting sustainable cooking practices. For instance, one notable technology that gained traction during this period is the development of efficient induction cooktops, which utilise electromagnetic induction to directly heat cookware, resulting in faster cooking times and reduced energy consumption (Snell, 2023; Sridhar, 2023). In addition, integrating renewable energy sources, such as solar PV systems, into e-cooking appliances has attracted substantial attention to reduce carbon emissions and promote energy independence (Energy Sector Management Assistance Program, 2020; Lecuona-Neumann et al., 2024). In addition, the implementation of environmental regulations, such as the Paris Agreement's goal adopted in 2015 under the United Nations Framework Convention on Climate Change (UNFCCC) to limit global temperature rise to well below 2 °C (Ganti et al., 2023; Voigt, 2023), and policy initiatives like the United Nations' Sustainable Development Goal 7, which aims to ensure access to affordable, reliable, and modern energy services (Matenga, 2022; Tucho & Kumsa, 2020), could have also sped up the adoption of sustainable cooking methods and the creation of clean cooking technologies.

Furthermore, after the peak in 2021, the number of articles published in 2022 and 2023 (14 each) remained consistently high, suggesting a sustained interest and ongoing research efforts in e-cooking. The increasing research output could lead to developing and refining new e-cooking technologies, making them more efficient, user-friendly, and accessible to a wider consumer base.

Figure 3 presents the frequency of articles published by different countries or regions. The results indicate that the United Kingdom (115 articles), the United States (87 articles), and Japan (25 articles) are the top three countries in terms of article production. This suggests that these nations have a strong research focus and interest in this field, which could be attributed to technological advancements, energy policies, and environmental concerns. The UK dominance could be due to the Modern Energy Cooking Services (MECS) programme initiative. The MECS programme, funded by UK Aid, drives research and innovation to transition developing nations in Africa, South Asia, and the Indo-Pacific from traditional biomass cooking to modern, sustainable alternatives such as clean cookstoves and e-cooking devices. It partners with organisations to conduct studies, pilot projects, and shape policies promoting the widespread adoption of these clean cooking solutions (Modern Energy Cooking Services, 2024). Interestingly, several developing countries, such as Nepal (15 articles), Tanzania (11 articles), Malawi (7 articles), Nigeria (7 articles), Ghana (6 articles), Kenya (6 articles), Indonesia (5 articles), and Bangladesh (3 articles), have also contributed to the research on e-cooking. This could indicate a recognition of the potential benefits of e-cooking technologies in addressing energy access, sustainability, and environmental challenges these nations face.

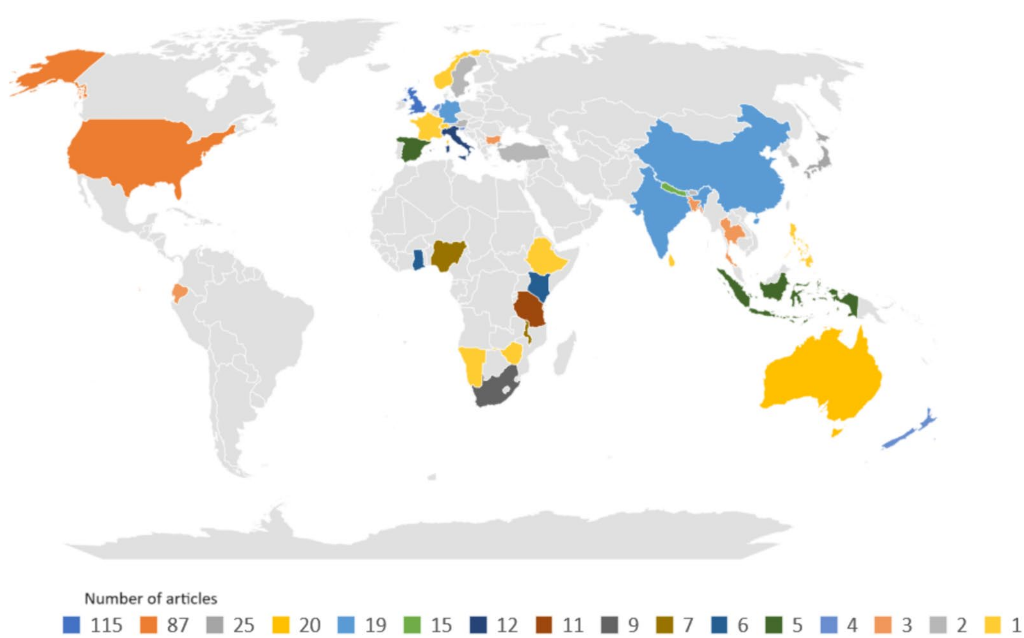

Fig. 3 Frequency of articles published by different countries

Study period thematic map, factorial analysis, and trend of topics

Figure 4 displays the thematic map. The thematic map categorises themes into four quadrants: basic, niche, motor, and emerging/declining themes, based on their relevance and centrality. The basic themes are characterised by high centrality but low density. The basic themes quadrant contains themes that are fundamental and highly central to the core topics of e-cooking and sustainable development. Words such as “clean cooking,” “e-cooking,” “and nergy access” fall into this category because they are essential concepts directly related to the main focus area. Similarly, the motor themes possess high density and centrality, indicating that they are well-developed and critically important to the research area. The motor quadrant contains highly relevant themes and is central to driving progress or innovation in the field. For instance, this quadrant includes words such as “life cycle assessment” and “e-cooking,” which are associated with renewable energy sources such as “off-grid,” “solar PV,” and “LCOE,” as they serve as significant drivers or enabling factors for sustainable e-cooking solutions. Likewise, the niche theme quadrant has high density but low centrality. The niche themes quadrant contains more specialised or niche-related themes for the broader topic. Words such as “fuel stacking,” “perceptions,” and “Tanzania” likely represent specific case studies, localised contexts, or niche aspects within the broader domain of e-cooking and sustainability. Furthermore, the emerging or declining themes quadrant represents themes that either emerge as new areas of interest or decline in relevance over time. The placement of the term “internet of things” here suggests that it is either an emerging concept or technology with potential implications for e-cooking and sustainable development, or it could be a theme that is declining in relative importance compared to other themes.

Figure 5 shows the results of the factor analysis. The figure displays words or terms, their corresponding scores or loadings on two dimensions (Dim. 1 and Dim. 2), and a cluster assignment. The scores or loadings on these dimensions indicate each word’s relative importance or contribution to that particular dimension. The results reveal a close clustering of topics such as “energy,” “electric cooking,” “sustainable development,” “mini-grids,” and “energy efficiency,” indicating a strong association or correlation among these concepts. Positioning this cluster in the positive quadrant of both dimensions indicates a positive relationship with the underlying factors represented by the axes. Conversely, the clustering of topics such as “gas emissions,” “greenhouse gases,” “carbon dioxide,” and “energy utilisation” in the negative quadrant of both dimensions suggests a negative association with the factors represented by the axes. This cluster is opposed to the e-cooking and sustainable development clusters, implying a potential trade-off or contrasting

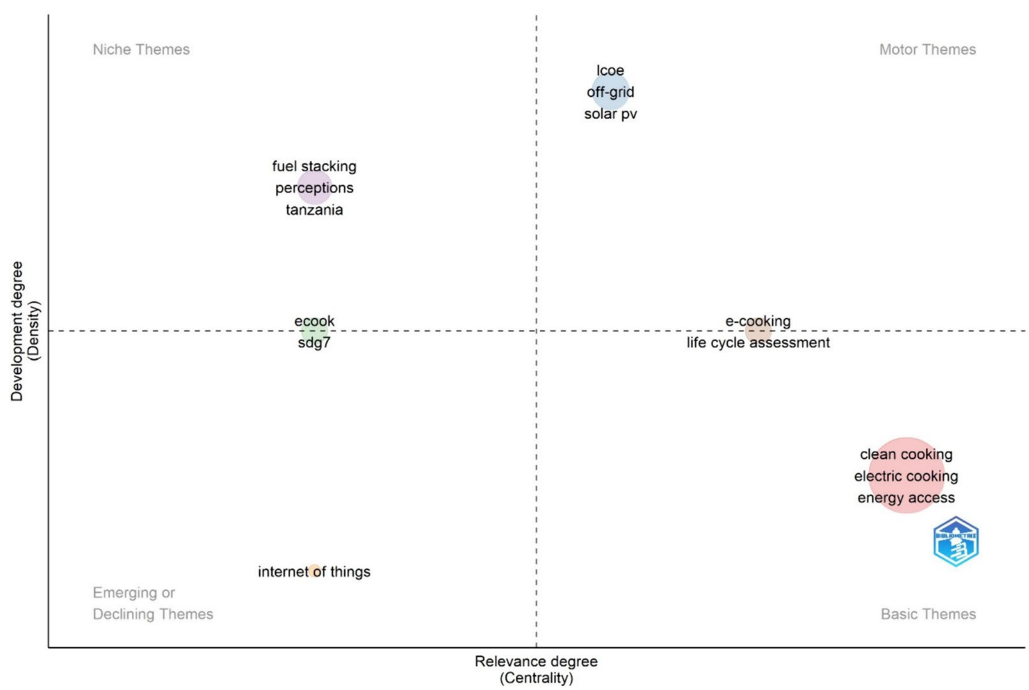

Fig. 4 Thematic map of keywords

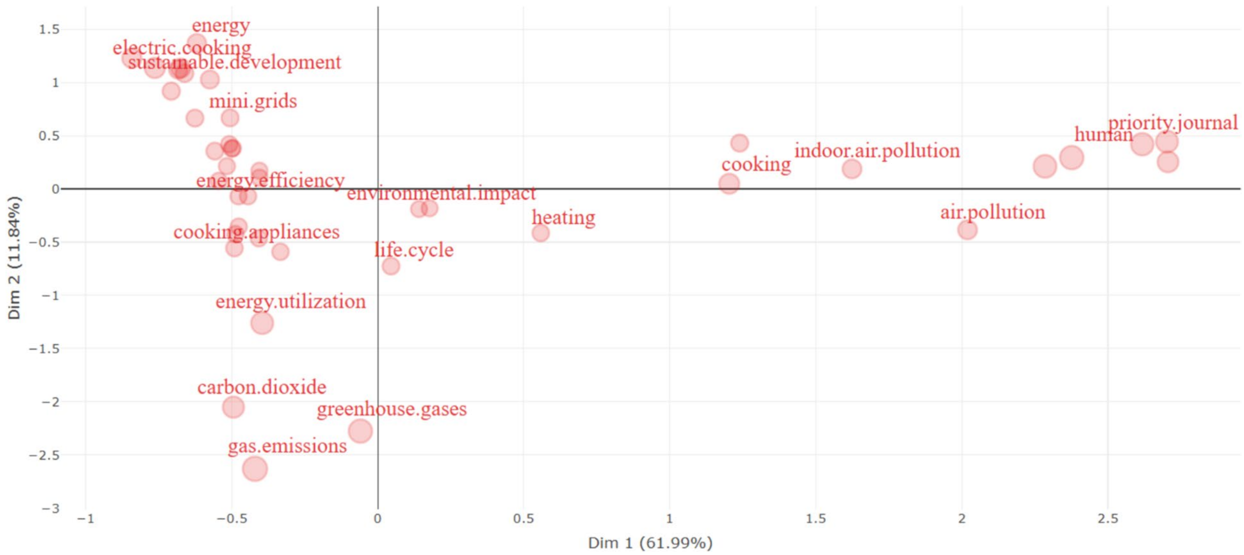

Fig. 5 Factorial analysis of author keywords

relationship between these concepts. The origin includes topics such as “cooking appliances,” “life cycle,” “heating,” “cooking,” “indoor air pollution,” and “air pollution,” suggesting a relatively neutral or mixed relationship with the underlying factors.

The results suggest that e-cooking and related concepts such as mini-grids, energy efficiency, and sustainable development are positively associated with the factors represented by the figure. In contrast, concepts related to greenhouse gas emissions and energy utilisation are negatively associated. These findings have important implications for promoting sustainable development and mitigating environmental impacts. The positive association between e-cooking and sustainable development concepts suggests that adopting e-cooking technologies, coupled with energy efficiency measures and deploying mini-grids or decentralised energy systems, could contribute to sustainable development goals. However, the negative association with greenhouse gas emissions and energy utilisation highlights the need to carefully consider the energy sources used for e-cooking and the life cycle impacts to ensure a net positive environmental benefit.

The trend of topics is shown in Fig. 6. The results cover many years, from the 1990s to the present (2023). The topics seem to evolve, highlighting the changing research interests and priorities. In the earlier years (1990s to early 2000s), topics such as “nitrogen dioxide,” “air pollution, indoor,” “humans,” and “female/male” were more prevalent. These topics suggest a focus on the health and environmental impacts of traditional cooking methods, mainly indoor air pollution and its effects on human populations. Around the late 2000s and early 2010s, topics such as “electricity,” “electricity generation,” “energy utilisation,” and “carbon dioxide” started to emerge. This shift indicates a growing interest in the energy aspects of cooking, particularly electricity use and its impact on GHG emissions. In more recent years (2018–2023), topics such as “liquefied petroleum gas,” “energy efficiency,” “life cycle,” “mini grids,” “clean cooking,” and “carbon” have gained prominence. These topics focus on cleaner and more sustainable cooking solutions, energy efficiency, and cooking activities’ overall lifecycle and carbon footprint. The presence of “Nepal” as a topic from 2019 to 2020 suggests that there may have been specific research or initiatives related to e-cooking in that country during that period.

Advancements in e-cooking for future research directions

This section synthesises findings from relevant studies on e-cooking development. It categorises e-cooking development into four areas: electric cooking and appliances, renewable energy integration and microgrid, socio-economic and behavioural aspects, and environmental and health impact.

Electric cooking technologies and appliances

The studies in this section highlight the importance of developing and evaluating various e-cooking appliances and technologies to improve their energy efficiency, performance, and user-friendliness. A key area of focus is comparing different heating principles such as induction, resistance, and radiative heating used in electric

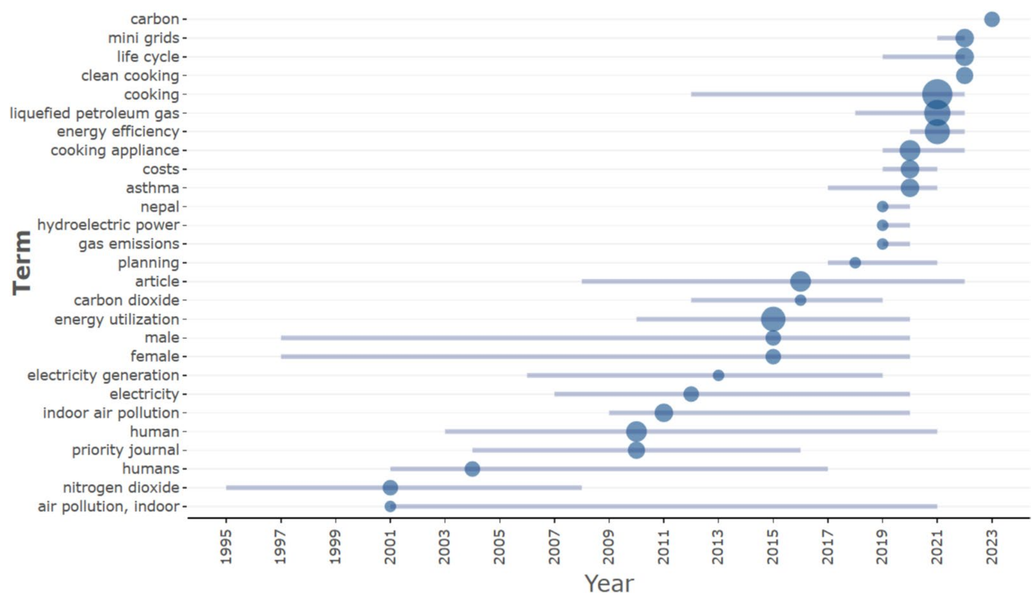

Fig. 6 Trend of research topics

cookstoves. For instance, Rose and Morawicki (2023) found induction cooktops and electric pots promising options due to their high energy efficiency, particularly for boiling water quickly. The authors further revealed that induction cooktops excelled at temperature control during simmering compared to resistance coils. However, while electric cookstoves have an end-use efficiency of around 80%, their total system efficiency suffers from inefficiencies in electricity production and transportation (Kashyap et al., 2023). To address this limitation, researchers explored integrating electric cookstoves with renewable energy sources like solar power, as shown in Figs. 7 and 8. Solar cooking has a higher total system efficiency since the end-use efficiency equals the total system efficiency (Kashyap et al., 2023). For example, improvised solar electric stoves using local materials can provide cost-effective solutions that perform similarly to commercial electric cookers (Cristobal, 2021).

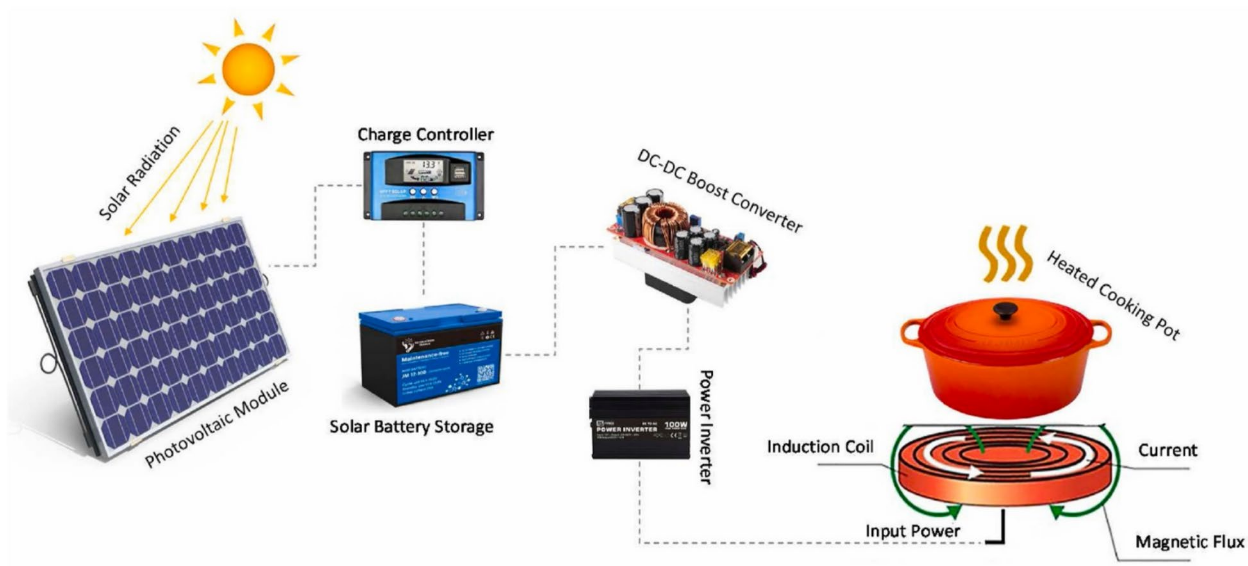

Fig. 7 Solar PV-induction cooking system with a hot plate (Altouni et al., 2022) (Reproduced with permission from Elsevier, License number: 5813551033518)

Fig. 8 Solar electric cooking system (Indiamart, 2024)

Siddiqua et al., (2016) developed a double-burner solar PV-powered electric stove suitable for rural areas. Khan and Alam (2020) proposed a cost-effective solution integrating solar PV with the grid and utilising hot water energy storage, reducing energy costs by 32% compared to grid-connected cooking systems. Altouni et al., (2022) investigated the performance of a PV-powered induction cooker, achieving energy efficiencies up to 47.6% at specific times, though cooking times were longer than LPG stoves.

Furthermore, another area of focus is pre-heating water using thermal energy storage, which can significantly reduce the electrical energy required for cooking. For instance, Chiloane et al., (2023) found that pre-heating water from 50 °C to 97.6 °C could reduce electrical cooking energy consumption by 12.36% to 27.79% when cooking rice. Further innovations include insulated solar electric cookers (ISEC) and pressurised solar PV electric cookers (PSEC) with phase change materials (PCM) like erythritol for energy storage, as shown in Figs. 9 and 10 (Opoku et al., 2022; Osei et al., 2021). These can enable rapid cooking by storing solar energy and even allow post-sunset cooking. The ISEC and PSEC technologies directly connect a solar panel to an insulated electric heater, thoroughly cooking meals while keeping food warm after initial heating to reduce firewood use and indoor air pollution (Watkins et al., 2017). Simon Prabu et al., (2023) revealed that integrating PCMs like coconut oil into solar cookers can provide energy storage for uninterrupted cooking during off-sunshine hours, demonstrating high effectiveness among PCMs tested.

Other approaches include developing standalone solar cookers (hotplates) powered by PV energy (Atmane et al., 2021), solar electric cookers directly connected to solar panels (Mok & Saigal, 2020), and PV-powered electric stoves for regions with inadequate gas supply (Islam et al., 2014). Accordingly, Ahmed and Khalid (2020) developed an Internet of Things (IoT-enabled) electric cooker incorporating inductive heating, rotation, tilting, and a robotic arm for automated cooking. Katwale et al., (2021) designed a smart ugali cooker for domestic cooking applications. The ugali cooker consistently met the design goal by cooking 500 g of flour within the expected timeframe. Singh and Singh (2019) suggested that integrating off-grid PV systems with low-energy-demand electric cookstoves can enhance access to clean cooking while simultaneously powering other residential loads. However, incorporating certain e-cooking technologies like electric pressure cookers with mini-grids in developing areas requires careful consideration of their power demands and efficiency impacts (Zimmerle et al., 2020).

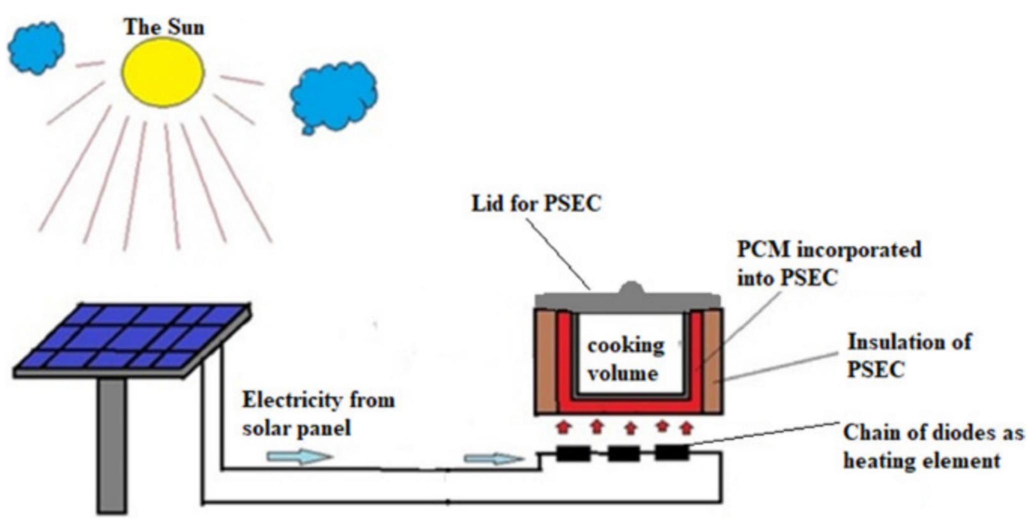

Fig. 9 Pressurised solar PV electric cooker using diodes as the heating element (Opoku et al., 2022) (Reproduced with permission from Elsevier, License number: 5813520834372)

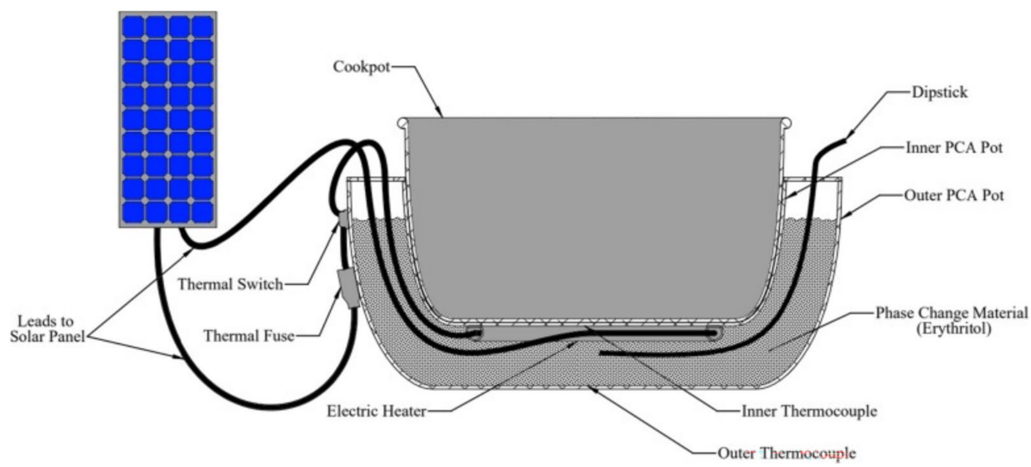

Fig. 10 Insulated solar electric cooker (Osei et al., 2021) (Published under open access)

Accurate performance measurement through standardised procedures and appropriate sensor choices is vital for assessing and comparing the energy efficiency of different e-cooking appliances to inform consumers and drive the adoption of efficient technologies (Beges et al., 2015).

Renewable energy integration and microgrids for e-cooking

This section explored the integration of e-cooking solutions with renewable energy sources, such as solar PV, and their application in microgrid systems. This integration holds promise for providing clean and efficient cooking options while expanding access to electricity in off-grid and rural areas. Several researchers have highlighted these integrated systems' potential economic viability and cost-competitiveness. For example, Dufo-López et al., (2012) found that off-grid PV systems with low-demand e-cooking can meet energy needs in rural areas at a levelized cost of around 3 cents per meal, indicating cost-effectiveness. In addition, Opoku et al., (2023) applied machine learning to use redundant energy obtained from solar PV mini-grid systems for cooking applications. The study revealed that redundant energy can be utilised to meet household cooking energy demand through sustainable thermal batteries. Among the machine learning models applied the K-nearest neighbour regressor demonstrated the highest accuracy, with a root mean square error of 0.148 and a coefficient of determination value of 0.998. Similarly, Lombardi et al., (2019) demonstrated the cost-competitiveness of a solar microgrid providing integrated access to electricity and e-cooking in Tanzania, with cooking costs ranging from 0.70 to 0.16 USD per meal, comparable to or even lower than options such as firewood and LPG. However, initial investment costs and monthly electricity expenses remain barriers to consumer adoption, particularly in rural areas with limited incomes (Clements et al., 2020). To address this, Clements et al., (2021) proposed innovative solutions like consumption-based payment structures instead of flat tariffs, which could increase utility income while incentivising households to reduce electricity usage. In addition, Eales et al., (2022) recommended demand-side management (DSM) strategies and smart cooking subsidies to accelerate the adoption of e-cooking on mini-grids.

Integrating e-cooking appliances into existing mini-grids presents challenges related to grid stability, voltage fluctuations, and limited capacity, especially during peak demand periods (Clements et al., 2020; Kweka et al., 2021; Silwal et al., 2020). Quetchenbach et al., (2013) demonstrated the effectiveness of GridShare technology and educational programmes in reducing severe brownouts caused by simultaneous e-cooking usage during mealtimes. To mitigate these challenges, Keddar et al., (2020) proposed innovative solutions like optimised PV/battery/diesel hybrid mini-grids, and Keddar et al., (2022) recommended smart battery management systems that monitor grid state and adjust battery charge rates to prevent voltage fluctuations and power losses. Furthermore, Keddar et al., (2021) developed a methodology for mini-grid developers to assess design readiness and future requirements for integrating e-cooking loads, taking into account factors such as fuel stacking, utilisation rates, and DSM strategies. Although e-cooking appliances demonstrated social acceptability and usefulness (Kweka et al., 2021), Dorward et al., (2022) emphasised the importance of understanding consumer charging and discharging behaviour, as well as novel cooking practices, for accurate power system modelling and expanding e-cooker usage, particularly in Sub-Saharan Africa.

Socio-economic and behavioural aspects of e-cooking

This category examines the socio-economic and behavioural factors influencing the adoption and acceptance of e-cooking solutions. It delves into consumer preferences, cultural barriers, affordability concerns, and the potential impact of e-cooking on employment and livelihoods.

Affordability and cost-competitiveness of e-cooking solutions

Affordability is a major barrier to adopting e-cooking technologies, especially in low-income households and communities. Several papers reviewed examined the affordability and cost-competitiveness of e-cooking solutions compared to traditional fuels such as firewood, charcoal, and LPG. Gius et al., (2019) demonstrated that direct DC solar electricity with a diode heater could make e-cooking cost-competitive with biomass cooking in many areas, especially as solar panel prices decline. Sánchez-Jacob et al., (2021) found e-cooking to be cost-competitive with LPG and charcoal in grid-connected households in Rwanda. Hakam et al., (2022) showed that in Indonesia, induction stoves are more economically advantageous than subsidised or non-subsidised LPG stoves, depending on electricity tariffs and subsidies. However, affordability remains a barrier in certain contexts. Keddar et al., (2022) found that exclusive e-cook battery cooking could match firewood costs only with low mini-grid tariffs and optimal battery sizing. Ensuring a sustainable and affordable firewood supply remains a challenge for economic competitiveness.

Some studies have highlighted the market potential and feasibility of e-cooking solutions, particularly in certain contexts with appropriate policies and interventions. With policy interventions like tariff adjustments, Shrestha (1995) suggested that e-cooking could be a viable demand-side management strategy in Nepal, particularly during certain seasons. Negi and Kumar (2018) found that increased penetration of energy-efficient technologies like e-cooking can influence and potentially reduce electricity demand across various sectors in India compared to a business-as-usual scenario. Pradhan et al., (2019) revealed that increasing the penetration of e-cooking options in Nepal can significantly reduce fuelwood and LPG consumption while lowering GHG and air pollutant emissions compared to a business-as-usual scenario. Coley et al., (2020) highlighted the potential for e-cooking in urban areas and on mini-grids in Malawi, while LPG remains viable in urban settings, but addressing knowledge and infrastructure gaps is crucial. Leach et al., (2021) found that e-cooking can be cost-effective and reduce human and ecological impacts in case studies in Zambia, Tanzania, and Kenya, with existing grids able to accommodate e-cooking. Ray and Chakraborty (2021) found that household cooperative efforts can decrease upfront investment costs for solar-PV-powered mini-grids with e-cooking and water treatment loads, enhancing overall feasibility. Sánchez-Jacob et al., (2021) suggested a stacking approach, combining electric and traditional cooking fuels, which could offer the most benefits of full e-cooking at a lower cost.

Socio-cultural factors and consumer behaviour influencing e-cooking adoption

Moraskar and Daigavane (2022) identified economic factors, fuel availability, awareness of traditional cookstoves' drawbacks, electric cooktops' benefits, geographical location, and social influences as potential challenges to adopting e-cooking. Bisaga and To (2021) suggested developing sustainable funding and delivery mechanisms for modern energy cooking solutions in displacement settings to improve displaced populations' access, health, and well-being. Paudel et al., (2023) identified several factors influencing households' preference for electric induction cooking in Nepal, including monthly expenses, electricity supply, cooking time, sickness rate, and environmental conditions. However, the study found the installation cost to be statistically insignificant. Households' minimum willingness to pay for electric induction cooking can reach 4% of their monthly income. In addition, introducing informational treatments to promote induction stoves boosts uptake rates by 5% and willingness to pay by 9.58%. Consumers' willingness to adopt clean energy is vital in shifting towards sustainable energy practices and achieving a carbon-free energy system (Afriyie et al., 2024). In view of this, Coley et al., (2020) identified weak infrastructure, consumer willingness and ability to pay, and resistance to adopting modern cooking devices as barriers in Malawi. Diemuodeke et al., (2021) emphasised the need to overcome technical, economic, policy, and socio-cultural barriers to widespread solar PV-induction cooking adoption in Africa. Ockwell et al. (2021) studied Lighting Africa's impact in Kenya and advocated for a socio-technical innovation system to achieve SDG 7. The study highlighted the limitations of the socio-technical integration system approach, including addressing gender disparities, considering technology scale implications, ensuring equitable benefit distribution to local actors, and understanding political and economic dimensions.

High upfront costs and monthly electricity expenses can make e-cooking solutions unattainable for many (Leary et al., 2021; Pelz & Urpelainen, 2020). However, innovative financing models like pay-as-you-go and subsidies could help improve affordability and access (El-Khozenadar et al., 2022; Kizilcec et al., 2022). In addition, research indicates that while the initial costs may be high, e-cooking can become cost-competitive against polluting fuels like charcoal over time (Batchelor et al., 2018; Saha et al., 2021; Van Buskirk et al., 2021). In view of this, Howells et al., (2006) analysed the South African free basic electricity (FBE) subsidy's influence on household energy choices, focussing on cooking preference distortion towards e-cooking. The study finds that the FBE subsidy drives electricity use in poor households despite cheaper alternatives like LPG. Proposing clean energy credits instead could enhance welfare by at least 6%. Khezri et al., (2022) evaluated the optimal sizing and economic analysis of rooftop PV and battery storage for grid-connected all-electric and gas-electric households under different system configurations. The authors found that the PV/battery system reduces the net present value more effectively for all-electric households than gas-electric households.

Beyond affordability, cultural preferences and awareness levels also significantly influence consumer adoption of e-cooking. Perceptions around taste, safety concerns, and reluctance from male decision-makers within households can hinder adoption (Leary et al., 2021). Some studies have suggested strategies to address this, such as awareness campaigns, peer marketing, and actively engaging men in decision-making. Adoption rates may be higher in contexts where households already purchase fuelwood or charcoal, have low-energy diets, and are familiar with low-power cooking devices (Brown et al., 2017). Other important factors that could be considered include gender dynamics and the potential impact on livelihoods. Shrestha et al., (2021) alluded that existing gender inequalities in household energy expenditure and the limited financial empowerment of women can impede the adoption of new energy technologies. Therefore, mainstreaming gender considerations in energy policy and increasing women's participation in the clean cooking workforce are recommended approaches. Lee et al., (2021) revealed that although e-cooking could create job opportunities in sales and distribution, there are currently skills gaps and low female participation (less than 30%) in this sector. Furthermore, consumer behaviour, particularly the practice of "fuel stacking" or using multiple fuel sources, is common and should be considered the norm rather than a transitional phase (Kizilcec et al., 2022; Price et al., 2021). In addition, electricity demand patterns are complex and influenced by appliance ownership, occupancy patterns, and socio-economic status (Scott & Coley, 2021). Therefore, understanding these local contexts and nuances is critical for successful e-cooking adoption.

Despite the challenges, some authors have also revealed opportunities and facilitating factors for e-cooking adoption. For example, convenience, potential savings from efficient appliances, and improvements in quality of life can drive consumer interest (El-Khozenadar et al., 2022; Leary et al., 2021). Brown et al., (2017) alluded that bundling e-cooking solutions with locally appropriate appliances that enable productive uses could further enhance adoption. Theoretical frameworks such as the Behaviour Change Wheel and Diffusion of Innovations can provide insights into consumer motivations and behaviour change strategies (Leary et al., 2021). Newell and Daley (2022a, 2022b) suggested supporting niche actors, building coalitions, rethinking behaviour change strategies, utilising state policy, and improving coordination among international actors to accelerate e-cooking adoption.

Environmental and health impacts of e-cooking

The studies in this area primarily focus on assessing the environmental and health impacts of transitioning from traditional cooking fuels such as gas, biomass, and kerosene to cleaner e-cooking solutions. Multiple studies demonstrate that gas cooking can contribute significantly to poor indoor air quality and associated health risks. Dennekamp (2001) found that gas combustion produces high concentrations of ultrafine particles (less than 100 nm) and nitrogen oxides (NO_2), especially when cooking fatty foods. Dick (2001) observed that particulate matter (PM10) from gas cooking induced pro-inflammatory effects in lung epithelial cells, potentially posing health risks, particularly for vulnerable individuals. Kornartit et al., (2010) and To and Yeung (2011) also reported higher levels of NO_2, PM10, and volatile organic compounds (VOCs) in homes using gas cookers compared to e-cookers.

In contrast, e-cooking solutions have been associated with lower levels of air pollutants and reduced health risks. Dai et al., (2021) found that households with no combustion sources, including e-cooking, had the lowest risks of persistent asthma, lung function decline, and bronchodilator reversibility over a 10-year period. Transitioning to e-cooking could also contribute to mitigating GHG emissions and achieving climate change goals. Yangka and Diesendorf (2016) estimated that promoting e-cooking in Bhutan's residential sector could reduce CO_2, SO_2, and NO_x emissions by 17%, 12%, and 8%, respectively, leveraging the country's hydropower-based electricity generation. Similarly, Im and Kim (2020) projected that by 2030, a 20% share of e-cooking households in Korea could decrease cooking-related GHG emissions by 3.8% despite population growth. Gould et al., (2023) found that the transition of over 750,000 households in Ecuador from gas to electric cookstoves likely decreased national GHG emissions by offsetting cooking gas combustion. In addition, introducing induction stoves correlated with reduced all-cause and respiratory-related hospitalisations nationwide, suggesting potential health benefits from the shift to e-cooking. However, it is important to consider the environmental impacts of the electricity generation sources used for e-cooking. In a life cycle assessment, Lee (2021) identified the major environmental impact of mini-grids sized for e-cooking as PV panels and suggested limiting diesel generators to 2 h daily for environmental benefits. From an environmental perspective, Bandekar et al., (2022) findings suggest that cleaner cooking methods such as electric pressure cooking and appropriate batch sizing can significantly reduce the environmental impact compared to open-vessel cooking or stovetop pressure cooking on electric ranges.

Summary and potential future research directions for the e-cooking sector

E-cooking technologies such as induction cooktops and electric pots have shown promise due to their high energy efficiency, especially when integrated with renewable energy sources like solar power, to improve overall system efficiency. The review indicates that integrating e-cooking solutions with solar PV and microgrids can be cost-competitive and expand access to clean cooking in rural areas. However, challenges remain around high initial costs, grid stability, and limited capacity during peak demand periods. Proposed solutions include optimised hybrid mini-grids, smart battery management, demand-side strategies, and innovative tariff structures. Although e-cooking powered by renewables offers significant potential to reduce GHG emissions and indoor air pollution compared to traditional fuels such as biomass and kerosene, affordability is a major barrier to consumer adoption, along with socio-cultural factors such as preferences, awareness levels, gender dynamics, and livelihood impacts. Therefore, understanding local contexts, "fuel stacking" behaviour, and employing behaviour change strategies are vital. Nonetheless, this review highlights e-cooking's environmental and health benefits while emphasising the need to address technical, economic, and behavioural challenges through a holistic approach for successful integration with renewable energy sources and widespread adoption. Further research is needed to address the technical, economic, social, and environmental aspects of e-cooking solutions in order to accelerate their adoption and contribute towards achieving sustainable energy access and clean cooking goals. Based on the current trends and advancements in e-cooking reviewed above, the study proposes the following areas as potential future research directions for the e-cooking sector.

Technological advancements in e-cooker design

This section's proposed future research directions include optimising solar e-cookers using artificial intelligence (AI) and integrating IoT and automation technologies. Solar e-cookers could be optimised using AI techniques such as machine learning and deep learning (Chauhan et al., 2022; Nazari et al., 2020). These techniques can be leveraged to develop adaptive systems that continuously monitor and analyse various factors, including solar irradiance, ambient temperature, and user behaviour, to dynamically adjust the cooker's settings for optimal performance, efficiency, and usability. For instance, machine learning algorithms can be trained on historical data and simulations to predict the cooker's performance under different conditions, enabling real-time adjustments to parameters such as the angle of the reflectors or the positioning of the cooking vessel (Anilkumar et al., 2023; Walke et al., 2024). In addition, deep learning models can be employed to analyse images or sensor data to detect potential issues, such as obstructions or misalignments, and provide corrective measures (Archana & Jeevaraj, 2024; Thakur & Mishra, 2024). Furthermore, reinforcement learning techniques can be explored to develop self-optimising systems that learn from experience and adapt their behaviour to maximise performance metrics such as cooking time, energy efficiency, or user convenience (Schwung et al., 2019; Töpfer et al., 2023).

IoT and automation technologies could be integrated into e-cookers to enhance user convenience, energy efficiency, and cooking experience. These technologies can enable remote monitoring, control, and automation of cooking processes, reducing manual intervention and enabling more efficient energy management (Hossein Motlagh et al., 2020; Yar et al., 2021). IoT-enabled e-cookers can be equipped with sensors to monitor various parameters, such as temperature, energy consumption, and cooking progress (Gerlée, 2018). These data can be transmitted to a central control system or a user's mobile device, allowing for real-time monitoring and remote control of the cooking process (Gerlée, 2018). Users can receive notifications, adjust settings, or even start or stop the cooking process remotely, enhancing convenience and flexibility. Automation technologies, such as programmable logic controllers or microcontrollers, can be integrated into e-cookers to automate various cooking tasks (A. Ali et al., 2021a, 2021b). For example, temperature and time-based cooking profiles can be pre-programmed or learned over time, ensuring consistent and optimal results while minimising energy waste.

Grid integration and energy management

Future research directions in this section comprise integrating e-cookers into smart grids and investigating demand-side management strategies. E-cookers could be incorporated into smart grid systems to enhance energy efficiency, demand-side management, and grid stability (Parvin et al., 2022; Sarker et al., 2021). Smart grid technologies, such as advanced metering infrastructure (Ghosal & Conti, 2019) and demand response programmes (Deng et al., 2015; Good et al., 2017), can facilitate two-way communication between e-cookers and the grid, enabling demand-side management strategies. In addition, e-cookers can be programmed to shift their peak load to off-peak hours or respond to grid emergencies by temporarily reducing their energy consumption by leveraging real-time pricing signals and demand response events. This demand-side flexibility can help balance supply and demand, improve grid stability, and promote the integration of intermittent renewable energy sources (J. Li et al., 2018; Santecchia et al., 2022). In addition, smart grid technologies can enable the implementation of dynamic pricing models, such as time-of-use or real-time pricing, incentivising consumers to shift their cooking activities to periods of lower electricity demand or when renewable energy generation is abundant (Öhrlund et al., 2019; Rodrigues et al., 2022).

Researchers can also investigate the impact of demand-side management strategies, such as time-of-use pricing and load shedding, on e-cooking adoption and grid stability. These strategies can influence consumer behaviour and energy consumption patterns, which in turn can affect the overall viability and success of e-cooking solutions (Shafiqa, 2023). Time-of-use pricing, which charges higher rates during peak demand periods, can incentivise consumers to shift their cooking activities to off-peak hours, reducing the strain on the grid (Muttaqee et al., 2024). However, the effectiveness of this strategy may depend on factors such as consumer awareness, perceived affordability, and the availability of alternative cooking options during peak hours (Takama et al., 2012). Likewise, load shedding, which involves temporarily reducing or interrupting power supply to specific areas or consumers during periods of high demand, can also impact e-cooking adoption (Ngoma et al., 2018; Wiese & Van Der Westhuizen, 2024). Although it may be necessary for grid stability, frequent or prolonged load shedding events can discourage consumers from adopting e-cooking solutions due to concerns about reliability and convenience (Kizilcec et al., 2022). To assess the impact of these strategies, comprehensive studies involving consumer surveys, energy consumption data analysis, and grid simulations can be conducted. In addition, pilot programmes and field trials can provide valuable insights into consumer behaviour and the practical implications of demand-side management strategies on e-cooking adoption and grid stability.

Socio-economic and gender considerations

The proposed further research directions in this category include assessing financial viability and exploring gender dynamics in e-cooking adoption. Researchers can assess the long-term financial viability of e-cooking solutions, particularly in low-income and rural areas. This assessment could consider factors such as tariff regimes, subsidy policies, and affordability for target populations. Tariff regimes are pivotal in determining the affordability of e-cooking solutions (Clements et al., 2020; Hakam et al., 2022). Progressive tariff structures, where rates increase with higher consumption levels, may discourage e-cooking adoption among low-income households. Conversely, subsidised tariffs or targeted subsidies for e-cooking appliances and electricity consumption can improve affordability and promote adoption. Subsidy policies and innovative financing mechanisms, such as pay-as-you-go or mobile-enabled fee-for-service models, could also enhance access to e-cooking solutions (Newell & Daley, 2022b). In addition, comprehensive cost–benefit analyses should be conducted to evaluate the long-term financial implications of e-cooking solutions, considering fuel costs, maintenance expenses, and potential health and environmental benefits. Moreover, researchers can delve deeper into the gender dynamics of energy access and the socio-economic factors influencing the adoption of e-cooking, focussing on designing inclusive policies and interventions. For instance, women are often primarily responsible for cooking and household energy management, making their perspectives and experiences crucial in shaping e-cooking solutions (Newell & Daley, 2022a; Perros et al., 2024). In this context, qualitative research methods, such as focus group discussions, interviews, and participatory approaches, can be employed to gather insights into the gender-specific barriers, preferences, and concerns related to e-cooking adoption. These insights can inform the design of e-cooking appliances, awareness campaigns, and capacity-building programmes tailored to address women's specific needs and challenges. In addition, socio-economic factors, including income levels, education, cultural norms, and household dynamics, can significantly influence the adoption of e-cooking solutions (Leary et al., 2021; Vassiliades et al., 2022).

Behavioural change and adoption strategies

This area focuses on developing theoretical frameworks and innovative business models to promote e-cooking adoption. Theoretical frameworks and models can provide motivational insights and guide the development of these interventions (Rosenkranz et al., 2023; Sekhon et al., 2017). Theories and models from fields such as psychology, sociology, and behavioural economics can be leveraged to understand and influence human behaviour related to e-cooking adoption. For example, the Theory of Planned Behaviour and the Norm Activation Model can provide insights into the factors that shape attitudes, social norms, and perceived behavioural control, which can inform the design of awareness campaigns and interventions (Liu et al., 2017; Setiawan et al., 2020). Likewise, community-based participatory approaches, where target populations are actively involved in designing and implementing interventions, can also effectively promote behavioural change (Trisnowati et al., 2024). These approaches can leverage existing social networks, community leaders, and cultural norms to disseminate information and encourage the adoption of e-cooking solutions. Similarly, future studies could explore innovative business models, such as pay-as-you-go or mobile-enabled fee-for-service models, to improve the affordability and access to e-cooking appliances and services (Newell & Daley, 2022b). Pay-as-you-go models allow consumers to pay for e-cooking appliances and services in small, regular instalments, reducing the upfront cost barrier (Schöne et al., 2023; Stritzke et al., 2023). These models can be facilitated by mobile money platforms or integrated with existing utility billing systems (Baker, 2023). Mobile-enabled fee-for-service models can provide access to e-cooking services on a usage-based payment structure, eliminating the need for significant upfront investments.

Fuel stacking approaches, where households use a combination of electric and traditional cooking fuels for different meals to provide most of the benefits of full e-cooking at a lower cost, is also another future research area where researchers can investigate (Sánchez-Jacob et al., 2021). Fuel stacking acknowledges that many households may be unable to transition completely to e-cooking due to financial constraints, infrastructure limitations, or cultural preferences (Nabukwangwa et al., 2023). Households can leverage the advantages of both systems while mitigating the challenges associated with each by combining e-cooking with traditional fuels. For instance, households could use e-cooking appliances for quick meals or dishes that require precise temperature control, while relying on traditional fuels for tasks such as water heating or cooking large quantities of food. This approach can reduce the overall energy demand and costs associated with full e-cooking while still providing improved indoor air quality, reduced drudgery, and increased convenience compared to traditional cooking methods. It is worth mentioning that, assessing the potential of fuel stacking approaches requires a thorough understanding of household energy consumption patterns, cooking practices, and preferences. Ethnographic studies, energy audits, and household surveys can provide insights into the feasibility and potential benefits of fuel stacking in different contexts.

Conclusion

This study provides a comprehensive overview of current research on e-cooking from 1993 to 2023 and its potential for contributing to sustainable development. The PRISMA guidelines were followed to examine papers for systematic review, and the biblioshiny package in R software was used to perform the bibliometric analysis. Between 1993 and 2009, the number of articles was low, with some years having none. A significant surge started in 2020, peaking at 23 articles in 2021. Publication numbers remained high in 2022 and 2023, indicating sustained research interest. The United Kingdom, the United States, Japan, Australia, and China are the top five countries leading in e-cooking research globally. However, some developing countries, including India, Nepal, Tanzania, South Africa, Malawi, Nigeria, Ghana, Kenya, and Indonesia, are among the top 20 countries leading research in this field. The thematic map analysis identified six clusters: clean cooking, cost of electricity, e-cook, fuel stacking, the Internet of Things, and life cycle assessments. Central themes were clean/electric cooking, energy access, mini-grids, and rural electrification. These highlighted the focus on sustainable, accessible e-cooking solutions, particularly for rural and off-grid areas, through decentralised systems. The systematic review revealed that e-cooking technologies such as induction cooktops, smart ovens, and electric pressure cookers offer promising solutions with high energy efficiency and the potential to reduce cooking time and emissions. Integrating these with renewable sources, particularly solar PV and microgrids, can provide cost-competitive and sustainable cooking options, especially in off-grid areas. However, affordability remains a major barrier, necessitating innovative financing models such as pay-as-you-go and subsidies. Socio-cultural factors, including consumer preferences, awareness, gender dynamics, and livelihood impacts, heavily influence adoption, requiring an understanding of local contexts and behaviour change strategies. Although e-cooking powered by renewables reduces GHG emissions and indoor air pollution compared to traditional biomass fuels, benefiting health, challenges exist around technical aspects such as grid stability with high e-cooking loads. Therefore, a holistic approach involving stakeholders, policy support, awareness campaigns, and technical solutions such as optimised hybrid mini-grids and demand-side management is crucial. The practice of using multiple fuels is widespread, so addressing "fuel stacking" behaviour is critical. Further interdisciplinary research is needed on optimising solar e-cookers, integrating Internet of Things/automation and innovative business models, assessing long-term financial viability, and exploring policy interventions to accelerate this transition while maximising sustainable development benefits.

Acknowledgements
The author acknowledges John Davis and Bernice Owusua Akwada for literature screening and data extraction.

Author contributions
FOY solely wrote the manuscript's main text, prepared all figures, and reviewed the manuscript.

Funding
This research received no specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Availability of data and materials
The data and materials used in this review are sourced from publicly available scientific literature, research publications, and reputable online databases. Any specific data or materials cited in the manuscript can be referenced by the corresponding author upon request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The author declares he has no competing interests as defined by Springer or other interests that might be perceived to influence the results and/or discussion reported in this paper.

Received: 14 May 2024 Accepted: 24 June 2024
Published online: 27 June 2024

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