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Biomass cookstoves: A review of technical aspects and recent advances

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ABSTRACT

The global increase in population coupled with poor access to clean energy has set pressure on solid fuel use. Through this, about one-third of the world's population currently relies on solid fuels (fuelwood, charcoal, coal, agro-residues, dung, etc.) in meeting their primary energy needs. However, only 11% of this population used improved biomass cookstoves (cookstoves with potential reductions in fuel use and toxic emissions). This is more peculiar to developing countries where cooking accounts for about 90% of domestic energy consumption. With this, research on cookstoves technology has increased in recent years as about 1905 articles have been reportedly published in less than a decade (2014–2022). This paper aims at bringing together literature spanning over a decade with a focus on the technical aspects of biomass cookstoves to establish the recent advances and current state of knowledge. Literature on different biomass cookstoves designs, operational features, and testing protocols have been reviewed. An overview of various cookstove performances was critically discussed with emphasis on thermal and emission performance. Having looked at the literature, pathways for future studies were recommended. This includes the incorporation of social factors such as end users' perceptions in the design and development phase. This will not just enhance the design process but may influence the cookstove adoption. Others are developing similitudes of the traditional models but in improved forms using locally available materials, as well as models that operate with solid and liquid biofuels.

1. Introduction

More than one-third of the world's population (2.8 billion people) rely on various forms of solid fuels (firewood, charcoal, dung, residues, etc.) and kerosene in meeting their energy needs [1]. Unfortunately, a majority of these solid fuel users cook with traditional open fires and inefficient cookstoves [2], primarily due to poor access to cleaner cooking devices or being unable to afford clean cookstoves. Burning biomass fuels in traditional cookstoves or open fires emit large quantities of household air pollution (HAP) including fine particulate matter ($PM_{2.5}$) and carbon monoxide (CO) [3]. There is also evidence of acute and long-term Nitrogen dioxide (NO_2) concentrations and personal exposures beyond the World Health Organization (WHO) indoor hourly (163 ppb) and annual (33 ppb) exposure limit [4]. This results in significant health disorders such as respiratory [5], blood pressure, and cardiovascular disorders mostly among women [6,7], as well as 3.2 million premature deaths per annum as of 2020 [8]. As most of the users of biomass and traditional cookstoves are domiciled in developing countries, especially those in Africa, the region is at greater risk [9]. With the large number of solid fuel users, the United Nations through its Sustainable Development Goal (SDG) 7, has made several advances in ensuring access to clean and affordable energy which includes the provision of clean fuel and cooking technologies. However, the least developed countries (LDCs) in Africa are still having the highest percentage of people without access to clean cooking [10]. This depicts how relevant this paper would be to researchers and technicians working on cookstove design and development in Africa.

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Nomenclature

ACCES	Africa clean cooking energy solution initiative
BCT	burn cycle test
BC	black carbon
CCT	control cooking test
CO	carbon monoxide
CO_2	carbon dioxide
DC	direct current
FST	firepower Sweep Test
g	gram
GACC	global alliance for clean cookstove
GDP	gross domestic products
GHG	greenhouse gas
Gt	gigaton
HAP	household air pollution
IoT	Internet of things
kg	kilogram
KPT	kitchen performance test
ΔL	learning and monitoring
LCA	life cycle assessment
LDCs	least developed countries
LED	light emitting diode
lit	liter
min	minute
MT	metric tonnes
NO_2	nitrogen dioxide
NGOs	non-governmental organizations
OC	organic carbon
PAC	portable air cleaners
$PM_{2.5}$	particulate matter
SDG	sustainable development goal
t	time
TBF	three brick fires
TEG	thermoelectric generator
TLUD	top-lit up-draft
TLDD	top-lit down-draft
U_0	initial level of acceptance
Umax	maximum level of use
Usat	level of sustained use
WBT	water boiling test
WHO	world health organization
WHT	water heating test

While over 80% of the population in Africa relies on solid biomass in meeting their cooking energy needs, only 11% of the population makes use of clean cookstoves and fuels [11]. This has undoubtedly contributed to deforestation and the current climate change crisis affecting the region. Though there have been various interventions put in place to address the aforementioned problems, they seem to be inadequate. Therefore, a critical intervention is required in extending the relevance of improved biomass cookstoves to local users and making the same available for free or at an affordable rate, especially in regions where the population has grown beyond the natural regenerative capacities of their local forests. It is important to note that fuelwood collection may not be minimized until a significant improvement in the use of efficient cookstoves is achieved [12].

As an approach to minimize the said challenges, improved biomass cookstoves were developed [13]. To emphatically state its significance, [14] observed that switching from the use of traditional cookstoves to improved cookstoves has a global emission mitigation potential estimated between 0.6 and 2.4 Gt of CO_2 per year. Similarly, [15,16], and [17] have all reported several benefits of the improved cookstoves over the traditional types. Although the transition from using traditional cookstoves to improved cookstoves has been quite slow due to a couple of reasons discussed in this paper, it is believed that when adopted, it would address a lot of shortfalls experienced in using traditional cookstoves. Thus, as an approach to improve energy use, especially in developing countries where cooking accounts for about 90% of domestic energy consumption [18], research interest in improved cookstove technology has increased in recent years. Based on this, about 1905 articles have been reportedly published between 2014 and 2022 [19].

Several studies have broadly reviewed different aspects of biomass cookstove technology, including the review of technical aspects [18,20], the review of technologies and programs [21], the review of state-of-the-art testing protocols [22], and directions to improve thermal efficiency [23], among others. However, a broad gap has been observed from the literature in terms of design and development, adoption and dissemination, health and environmental impact, and fuel type for powering the cookstoves. The novelty of this review is that it reports the most recent advancements in cookstove research as well as pathways to address the observed gaps.

Against this background, the objective of the present review is to provide an overview of the technical aspects of biomass cookstoves including the recent advances to establish the current state of research in the cookstove sector. It is believed that the paper would serve as a guide to researchers, technicians, cookstove manufacturers, policymakers, and organizations interested in aiding cookstove adoption and dissemination as well as current and potential biomass cookstove users.

The reviewed articles were sourced from Scopus, Google Scholar, and Science Direct databases to ensure a collection of purely indexed articles. Keywords such as biomass cookstoves, improved cookstoves, and cookstove design and development were used in searching the articles using a filter date of 2010 to 2023. It was ensured that only research and review articles dealing with the technical aspects of biomass cookstove development were considered. Hence, the literature was screened based on titles and abstracts, and about 250 articles were downloaded. The review methodology was based on exhaustive literature analysis keeping in view the recent advances in biomass cookstove development. Some major research gaps have been observed from the reviewed articles and recommendations have been suggested for future investigation.

2. Biomass energy

Biomass is non-fossilized and biodegradable biological material derived from living organisms, animals, and plants [24]. It is typically composed of lignin, cellulose, hemicelluloses, and extractives like fats, resins, and ash [25]. Biomass is considered a sustainable and carbon-neutral source of energy because it is a renewable energy source whose fuel cycles are neutral in terms of greenhouse gas (GHG) emissions. The most common way of utilizing biomass, especially in low-income countries is by directly combusting it as fuel in cookstoves [26]. Others include physical conversion into pellets and briquettes as discussed in [27], biochemical conversion into biogas, and thermochemical conversion through gasification and pyrolysis, among others. Several studies have reported the successes of processed biomass. They include biomass to pellet [26,28], biomass to briquette [27,29,30], biomass to sound absorption panel [31], biomass to biogas [32,33], etc. However, this paper is limited to the sustainable use of biomass as energy or fuel in improved cookstoves, as it is perceived as a measure of abating the emission of harmful gases to the environment and mitigating climate change. Sustainable use in this context, involved ensuring a balance between harvested and regrown biomass to avoid negative environmental impacts [34].

Since ancient times, biomass has been a major source of energy for industrial and domestic use, particularly in developing countries [18, 34–36]. However, as technology advances, the use of fossils has rapidly overwhelmed the use of biomass, especially in urban parts of the globe, resulting in a series of environmental concerns [38]. Thus, as the population increases, fossil fuel reserves are gradually depleting and making fossils more expensive and unaffordable. This has made biomass the major source of energy in most rural and peri-urban households. Based on its extent of use, it is considered the most important renewable energy source globally [24,38,39]. In recent years, biomass and biomass energy have shown promising and sustainable features that made it one of the major and affordable renewable energy sources [40]. Some common biomass used as primary energy sources for cooking in developing countries includes charcoal, fuelwood, crop residues, cow dung, etc., [41]. However, it is important to note that, despite being a renewable energy source, it also emits harmful gases when used in traditional open fires or cookstoves. On this basis, about 1.9 - 2.3% of the global CO_2 emissions come from the use of fuelwood [42]. In South East Asia, about 85% of Black Carbon (BC) and approximately 100% of Organic Carbon (OC) emissions emanate from the use of solid biomass especially charcoal [43]. Going by the large percentage of biomass and traditional cookstove users in Africa, cooking-related emissions are expected to be higher than the reported values. The intensity of biomass use in Africa is not unconnected to the lack of access to clean and affordable energy in the region.

Although as a form of renewable energy, the use of biomass is encouraged over fossils, lignocellulosic biomass has been suggested over tree or woody biomass. However, in areas where the lignocellulosic biomass is insufficient, sustainable use of the tree biomass is encouraged. This is to ensure that the environment and ecosystem are preserved. In most parts of Africa, biomass is directly combusted as fuel. Even with this, [44] revealed that fuelwood emits higher than some lignocellulosic biomass like corn stalks and wheat straw. Now that studies have advanced in clean cooking, biomass is being processed into biofuels like briquettes, pellets, biogas, etc., and are being encouraged over the use of loosed biomass and products of tree biomass (fuelwood and charcoal). This is because, in recent years there has been a rapid population increase, based on which the use of tree biomass has increased with limited attention to regrowth or regeneration, resulting in forest degradation [45]. In addition to using lignocellulosic biomass and ensuring the regrowth of tree biomass, measures such as the use of energy-efficient cookstoves are perceived as being effective in saving fuel use and by extension deforestation. Therefore, setting out policies such as placing a ban on fuelwood collection and charcoal production will go a long way. With this, people would be compelled to utilize their generated lignocellulosic biomass residues as fuel instead of routinely encroaching on the forest.

3. Biomass cookstoves

3.1. *Types of cookstoves*

Over the years, different types of cookstoves have been developed. The innovation stems from open flame fires to three brick fires (TBF) and metallic shielded models to improved and advanced cookstoves [20], as shown in Fig. 1. The effort to develop improved cookstoves began as far back as the 1950s when it begins with technological attempts to upgrade the design of the then biomass-powered cookstoves. In the 1970s the development of improved cookstoves started as a way of augmenting the oil crisis and solving the fuelwood crisis thought to curb deforestation and desertification [46]. Although there are several models and types, cookstoves are broadly classified as traditional (Fig. 1 a–d) and improved (Fig. 1 e–h).

3.1.1. *Traditional cookstoves (primitive designs)*

Traditional cookstoves are designed in rudimentary or primitive forms. They are characterized by having low fuel, thermal, and emission performance [3,50,51]. Because they are poorly designed without adequate combustion metrics, fuels are not properly combusted, hence, resulting in high emissions [52,53]. This, as reported by Africa Clean Cooking Energy Solution Initiative [55] leads to an annual mortality rate of nearly 600,000 in Africa with millions of chronic illnesses. Out of the 3.4 million hectares of forest land lost annually in the region [56], Cooking with traditional cookstoves and open fires, results in an annual loss of about 500 million tons of non-renewable wood [57].

Fig. 1. (a) Three stone open fire, (b and c) metallic open fire, (d) traditional charcoal stove,
(e) Natural-draft double burner biomass cookstove [47], (f) husk biomass cookstove [48], (g) Inverted downdraft gasifier cookstove [49], (h) Improved biomass cookstove [50]

3.1.2. Improved cookstove (advanced designs)

The improved cookstove models are advanced designs developed to cushion the drawbacks of traditional cookstoves [57,59]. The word "improved" signifies potential reductions in fuel use and toxic emissions, though the potential benefits is beyond that as it includes safety, cost reduction, and time savings among others [57]. Most of the improved cookstove designs primarily target fuel, thermal, and emission performance [60]. With this, [61] believed that for a cookstove to be considered improved, it must be able to curtail $PM_{2.5}$ emissions by at least 50%. Generally, improved biomass cookstoves are classified based on performance, mode of combustion, and type of construction material [17]. Based on this, some are designed as Top-Lit Up-Draft (TLUD) [62], i.e. lit from the top with primary airflow coming from the bottom to the top. While some are Top-Lit Down-Draft (TLDD) [48,61] (Fig. 1g), i.e. lit from the top with primary airflow coming from the top to the bottom. Others include, natural draft design [47] (Fig. 1e), force draft design [3], or a combination of both [62,63]. In terms of feeding methods, there are batch-fed [66], i.e. designs that involve feeding in fuel and allow it to burn completely before feeding in another and designs that are fed continuously with fuel [49,65].

Literature has reported the performances of the various models in comparison to the conventional traditional models. Some studies that reported the superiority of improved cookstoves include that of [68] which discovered that the improved cookstove tripled the traditional open-fire stove in performance with a fuel saving of more than 60%. Similarly, [69] reported a 40% fuel saving while in a different study, a 30–60% fuel saving was recorded [17]. In another study by [70], a 79% fuel saving was achieved. [15] compared the fuel use and emissions of different improved cookstove types with three-stone open fire. The study revealed a reduction in fuel use by one-third, CO emissions by three-fourths, and PM emissions by almost half in a rocket stove. While, gasifier stoves under effective operation, yield a 90 % improvement in terms of PM emission reduction. Forced-air stoves with small fans reduced fuel use by an average of 40 % and emissions (CO and PM) by 90%. In another study, black carbon emissions were lowered by 50 - 90 % using an improved biomass cookstove [17]. While the nature or type of biomass cookstove design affects the cookstove's performance, the actual cooking process equally contributes to the performance, particularly the emission of gases. Based on this, [37] revealed that when biomass cookstoves are used for boiling and frying, they emit more gases compared to when used for baking and sautéing. Hence, future designs may include a balancing factor that will unify the various operational processes under low emission.

Despite the enormous benefits of improved biomass cookstoves on the health of their users and the environment, the developed models and designs have received less attention from many parts of the world where the use of traditional cookstoves is high, including the scientific and technical communities [20]. This has been validated in several studies focused on improved cookstove adoption, including [71] conducted in Kenya, where only 38.5% of households were found to have adopted improved cookstoves. Similarly, in Ghana, a low adoption rate was reported based on a preference for traditional models and unwillingness to switch to improved models, majorly because they are not available in local markets [72]. Overall, as reported in the literature, developing countries are dominated by traditional cookstoves. Out of the 166 million households that used improved cookstoves globally, 116 million are in China, more than 13 million are in East Asia, about 22 million are in South Asia, and about 7 million are in Sub-Saharan Africa [73].

Table 1 shows some improved cookstove models and their features as related to fuel saving and emission reduction.

3.2. Improved cookstove design and development

Over the years, researchers have worked enormously on developing clean cooking technologies that are fuel efficient and less emissive to address the drawbacks of the traditional cookstove models. Through this, several models of improved biomass cookstoves were developed. However, there is still a wide gap in terms of following systematic design approaches, including modeling and lifecycle analysis of the various design and development phases [41]. Bridging this gap will not only ensure the selection of the best materials but will give a clearer picture of the potential environmental impacts of the materials as well as the developed cookstove. Another area that will improve the performance of cookstoves is to consider optimizing the design process. While this has not been given prompt attention over the years, it is imperative to note that design optimization has been recommended as one of the best methods of minimizing cost and maximizing the performance of developed systems or processes.

The first approach in designing an improved biomass cookstove is to select the fuel type it will operate with [23]. In this phase, the designer decides on making it a single-fuel or multi-fuel type, based on which the combustion chamber will be designed. Though all the cookstove components are essential and are expected to be designed appropriately, the combustion chamber, being the heart of the cookstove where the thermal processes take place must be given extra attention [18]. Thus, it is important to carefully design the combustion chamber and select the appropriate material that will conserve heat and improve heat transfer from the combustion chamber to the cooking medium. Other features such as the geometry of the stove and pot, fuel type, and available space between the pot and stove are equally essential [79]. Furthermore, as shown in Fig. 2, the heat transfer process depends on the stove insulation and cladding which if wrongly designed would increase heat loss and fuel consumption. On this note, different cookstove construction materials have been evaluated and recommended.

3.2.1. Cookstove construction materials

The material selection phase of cookstove design is very vital to achieving a thermally efficient cookstove. There are different types of materials used in cookstove construction and they differ in characteristics as highlighted in Table 2. Hence, it is important to carefully review

Table 1
Operational features of selected cookstove types as related to fuel efficiency and emission reduction.

Cookstove Type	Fuel	Mode of Flow	Insulation Type	Fuel Saving	Emission Reduction			Refs.
					CO_2 (tons/yr)	CO (%)	PM (%)	
ND Improved Biomass	W	ND	CI	35 %	0.65	NA	NA	[60]
Enhanced Traditional (with twisted tape assembly)	W	ND	NA	21 %	NA	NA	38	[74]
Biomass Gasifier	W	ND	AI	NA	1.30	NA	NA	[75]
FD Improved Biomass	BF	FD	AI	49%	NA	30-74	21-57	[76]
Twin Mode Gasifier Biomass	W, BP	ND, FD	RC	NA	6.89-7.04 (FD), 6.65 (ND)	NA	NA	[65]
Nozzle Type Improved Wood	W	ND	GW	NA	26.42	NA	NA	[77]
Improved Biomass (Udairaj)	W	ND	NA	700 kg/yr	0.161	NA	NA	[78]
Biomass Gasifier	W	ND	RC	4500 kg/yr	7.16	NA	NA	[51]
Rocket-type (Tikikil)	W	ND	RC	43%	1.3	42	99.5	[52]

Note: W = wood, BF = Biomass Feedstock, BP = Biomass Pellet, GW = Glass Wool, NA = Not Available, ND = Natural Draft, FD = Forced Draft, CI = Ceramic Insulation, AI = Air Insulation, RC = Refractory Cement

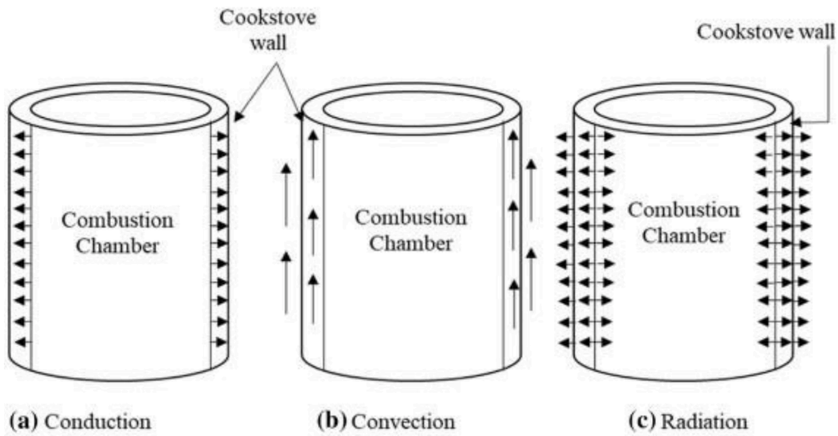

Fig. 2. Cookstove heat transfer process [79]

Table 2
Characteristics of some cookstove construction materials [80].

Material	Merits	Demerits	Possible Utilization
Clay	- Low cost - Widely available - High service and melting temperature(1000-1700°C) - Low thermal expansion - Can be cast into different shapes	- Low strength - Density varies depending on the type - Thermal conductivity varies depending on the type - Difficult to determine the type/quality of clay - Long drying and curing time (2-3 weeks) - Requires controlled firing at high temperature	- Combustion chamber/refractory liner
Aluminum	- Easy to machine or form - Low density - Moderate strength - Reflective foil can be used for radiative insulation	- High cost - Very high conductivity - Low availability - Low service and melting temperature (250°C)	- Radiative insulation
Cast iron	- High strength - High service and melting temperature - Can be cast into different shapes	- High cost - Very high conductivity - Low availability of scrap iron - Melting and casting are difficult	- Cone deck and pot supports - Grate
Mild steel	- Low cost - Widely available	- Low service and melting temperature - Poor corrosion resistance	- External components (door, handles, legs, etc.)
Cement	- Moderate cost - Widely available - Can be reinforced w/ aggregate or steel wire to provide strength - Can be cast into different shapes - Low thermal expansion	- High density - High thermal conductivity - Long drying and curing time (3-7 days) - High environmental impact	- A binding additive in an insulating mixture

the features and select them appropriately. By and large, cookstove materials should be selected based on performance (energy efficiency, safety, durability, time, etc.), affordability (service life, unit cost, fuel consumption, etc.), and usability (ease of ignition, portability, time saved, cleanliness, and the user interface) [40,78].

Traditional cookstoves are largely constructed with clay, cement, or bricks, while improved cookstoves are mostly made of metallic-based materials (stainless steel, galvanized steel, mild steel, aluminum, etc.) accompanied by less thermal conducting materials as insulators. The choice of metallic materials for the latter is to attain low thermal inertia, ease usability and maintenance, as well as enhance durability [20]. However, metallic materials are mostly employed for stove cladding and grate construction, while materials such as ceramic, fiberglass, concrete, and cement have demonstrated good performance as internal liners or insulators. Though ceramic insulators are commonly used, the material is not suitable for use as cookstove cladding because it is very fragile in nature [81] and hence, will not give a durable cookstove. For grate construction, [11] revealed that a stove with a ceramic clay grate performs better than those with aluminum and mild steel grates. In line with this, [47] used a 5mm mild steel sheet for constructing the grate which was further insulated with ceramic to control heat loss from the base of the combustion chamber.

3.3. *Cookstove testing protocol*

Cookstove testing is a very crucial aspect of cookstove development. In this stage, a newly developed cookstove is subjected to at least one or more tests to validate its performance. The protocols widely used for cookstove performance testing are the water boiling test (WBT), kitchen performance test (KPT), and controlled cooking test (CCT) [18]. However, studies are underway to develop more protocols. These include; the burn Cycle Test (BCT), Water Heating Test (WHT), and Firepower Sweep Test (FST) [22].

While WBT is purely a laboratory-based test, CCT is performed both in the laboratory and on the field, whereas KPT is purely a field-based test. As shown in Fig. 3, the laboratory test (WBT) is the most commonly used, because it is easier, quicker, and less costly to conduct [18], and also provides a simple simulation of standard cooking procedures [82]. Another reason that made it popular is the presence of an officially published detailed protocol containing the testing concept and procedure, including the rationale and formulation of metrics in a well-simplified form [22]. The test is used for evaluating the performance of cookstoves by boiling a known quantity of water in a controlled environment [83]. It has several versions, viz: 3.0, 4.1.2, 4.2.2, 4.2.3, etc. WBT has two phases, viz: high power phase and low power phase. The high-power phase is further classified into two, viz: cold start phase (CS) and hot start phase (HS), while the low power phase is referred to as the simmering phase (SP). The cold start phase begins with the water and the stove at room temperature, where the water is gradually heated to local boiling temperature. While the hot

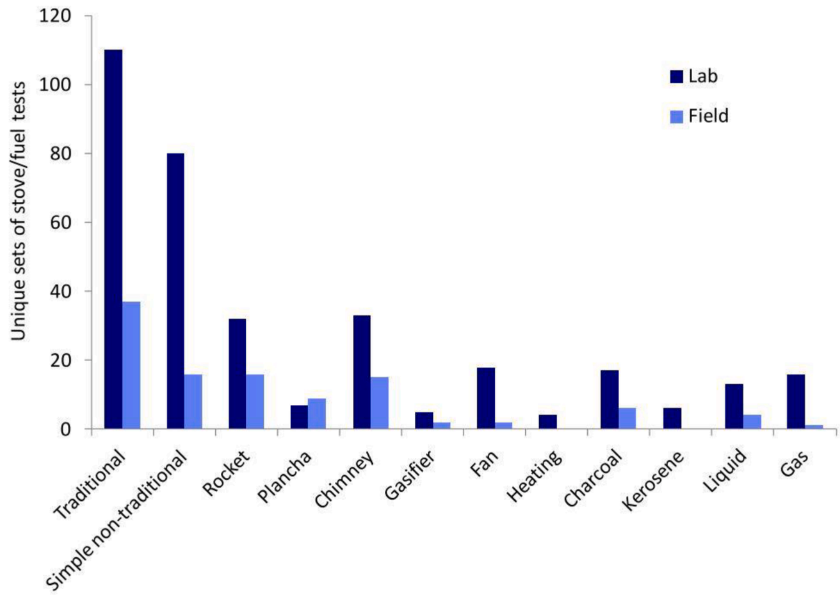

Fig. 3. Number of test sets for different stove and fuel characteristics [87].

Table 3
Summary of performance of different cookstove models.

Stove Type	Test Protocol	Major Construction Material(s)	Performance			Remark	Refs.
			TE (%)	FP (kW)	SFC		
The Apeli: Advanced Biomass Cookstove	ISO 19867-1	Ceramic	38-44.1	0.53-1.12	NA	It is important to validate the performance following conventional testing protocols like WBT or CCT	[67]
Forced Draft Charcoal Stove	WBT and CCT	Mild Steel	36.74	2.26	NA	The incorporation of supplemental air pack improved thermal efficiency by 12.23%	[89]
Household Gasifier Stove	WBT	Sheet Metal	17.2	NA	47.04g/min	The thermal efficiency is below the BIS 13152 (Part 1): 2013 minimum benchmark (25%).	[90]
TEG powered forced draft cookstove	WBT	Stainless Steel	44	1.1	NA	The cookstove performs best in the high-power hot start phase.	[91]
Improved Biomass Cookstoves Model- 1 and Model-2	WBT	Stainless Steel, Mild Steel	30.85 32.25	4.03 4.10	0.1305 0.1295 (kg/kg)	The performance of model-1 is lower possibly because the thermal conductivity of stainless steel is lower than that of mild steel	[92]
Twin Mode Biomass Gasifier Cookstove	NA	Mild Steel	36.7 33.44	2.95^{FD} 2.5^{ND}	NA	There is no significant difference between the performance in both natural and forced draft mode	[65]
Inverted Downdraft Gasifier Cookstove	WBT	Stainless Steel, Galvanize Steel	30.5-38.1	4.7-4.9	138-627 g/lit	As rice husk yields good performance, it is important to test more biomass fuels	[49]
Improved Double Burner Natural-Draft Biomass Cookstove	WBT	Stainless Steel	33	0.458-3.324	0.019 - 0.089 (kg/kg)	Double burner to suit all forms of biomass fuels. Additionally, major components were made detachable	[47]
Improved Wood Stove	WBT	Mild Steel, Clay, Fiberglass	64.4	7.59	0.447	The double insulation layers (clay and fiberglass), improve overall heat performance.	[93]
Natural and Forced Draft Biomass Cookstove	WBT CCT	NA	18.71^{ND} 25.93^{FD}	1.66 2.30	0.297 0.273	The average thermal efficiency for ND is below the minimum benchmark	[64]
Hybrid Solar-Biomass Cook Stove	WBT	Mild Steel	39 - 43	2.1	38 - 42 g/lit	Although the installation of a solar reflector to the cookstove improves thermal efficiency by 5%, this comes with additional cost and may not suit environments with low sunshine hours	[94]
Improved Biomass Cookstove	WBT	Stainless Steel	35	5.5	88 g/lit	Although the performance is within the tier 2 to 3 benchmark, a change of insulation from air to another medium may yield better efficiency	[68]
HDHR Cookstove	WBT	Granite Rock, Stainless Steel	28.8	1.57	47 g/lit	While the granite rock aided heat conservation, the cookstove has insufficient air inlets	[70]
Whirl Cookstove	WBT	Stainless steel Metallic mesh	68	5.6	NA	The whirl concept is good but appears to be highly dependent on airspeed. With that, it may not suit natural draft cookstoves.	[95]
Three pots improved cookstove	WBT	Brick	34.45	1.72	NA	The current brick design has shown good performance, however, having it fixed may affect routing maintenance, transportation, and performance especially as it is a natural convection stove. Thus, a portable and movable design should be developed	[12]

Note: LED = Light Emitting Diode, TEG = Thermo Electric Generator, WBT = Water Boiling Test, CCT = Control Cooking Test, ND = Natural Draft, FD = Force Draft, HDHR = High Density Heated Rock, NA = Not Available start phase is carried out when the cookstove is hot to simulate the cookstove's performance when hot. In the hot start phase, the water and fuel used in the previous phase are replaced with another set (same weight) at room temperature [62]. This will distinctly reveal the difference between the performance when ignited at room temperature to that at high temperature. The third stage (the simmering phase) provides information about the amount of fuel needed to simmer a specific amount of water below its local boiling temperature [62]. This phase simulates the actual cooking process, especially in the case of legumes.

Unlike the laboratory test which is performed in a controlled environment, the field-based test is difficult to control and may be subjected to errors. However, they have the advantage of reflecting the true state of fuel consumption in cookstoves [84]. KPT is a field test developed for use alongside the WBT and CCT. It compares fuel consumption in conventional stoves with those of improved or alternative stoves [60]. The CCT on the other hand focuses on evaluating the cookstove at the level of the end user. It is a measure to estimate the actual performance specifically the fuel-saving aspect and cooking time [83,85,86]. It further bridges the gap between laboratory evaluation and actual field performance.

In addition to the aforementioned testing protocols, [88] emphasized the need to subject cookstoves to tipping/sliding/spilling tests, as it evaluates the mechanical stability of the stove/pot combinations. This is very crucial as it provides information on the safety of the cookstove against direct injuries, accidental fires, liquid and food burns, contact burns, and scalds, among others [88]. In Table 3, the performance characteristics of different cookstove models are reported. This includes the test protocol, major construction material, and key performance output.

3.4. Overview of performances of different models of improved cookstoves

Cookstoves perform differently depending on their types, construction material, and mode of air circulation (natural or forced draft). Table 3 summarizes the performances of various cookstoves models.

4. Recent advances in cookstove research

The cookstove sector has recorded several advances in recent years. This has been occasioned by the growing interest in cookstove research especially in trying to meet up with SDG 7. Some of the recent advances include the provision for generating electricity from waste heat coming from cookstoves for powering small electrical devices with the aid of thermoelectric generators (TEG) [45,94–96]. Here, the TEG is connected to a stove (heat source) where it receives heat directly with the aid of thermoelements (p and n) and stores it in a heat sink where it gets converted to electricity (Fig. 4). Other advancements include the use of Internet of Things or IoT-enabled devices in efficiently controlling emissions from cookstoves during cooking [98], the use of biomass pellets to power cookstoves as an approach to combat climate change [99] and, battery supported eCooking approach [100], among others. Table 4 highlights some of the recent advances in cookstove research.

The stated technological advancements have impacted the rate of deforestation and climate change. On average, between 2007 and 2016, about 11.2 ± 2.6 gigatons of CO_2 is absorbed annually by the global forest [101]. Also, as mentioned earlier, several studies have reported the performance of improved cookstoves in terms of thermal efficiency and fuel saving. As technology advances, a higher percentage of fuelwood and charcoal are reportedly saved. This translates to deforestation reduction and improved carbon sequestration, which ultimately mitigates climate change. To affirm the stated claim, [102] reported that a single improved cookstove has the potential to reduce about 0.06ha of woodland deforestation thereby mitigating around 9.21MT of CO_2 emission per year.

5. Adoption and dissemination of cookstoves

As cookstove research and development keep growing over the years, adoption and dissemination are reportedly slow. While several articles have identified socioeconomic, education, demographic, technical, institutional, and contextual factors as the factors affecting the adoption of improved cookstoves [69,70,107,108]. Some believed that geographical, environmental, and fuel availability also influences clean cookstove adoption [71]. Overall, the adoption of improved cookstoves is perceived to be gradual and not a one-time process [58]. On this note, as shown in Fig. 7, the process of adoption is expected to start with initial acceptance at the household level (U_0) and progress steadily to a level of sustained use (Usat) under close learning and monitoring (ΔL) over time (t). With this, users are expected to maintain sustainable usage at their maximum level of use (Umax), and not to revert to the level of dis-adoption [110]. While cases of dis-adoption are commonly reported among households who were issued the cookstoves for free through interventions [111]. A long-term dis-adoption was observed among households that purchased the cookstove. The current paper has highlighted the following (sections 5.1 and 5.2) as some limiting factors to cookstove adoption and potential measures of scaling up adoption.

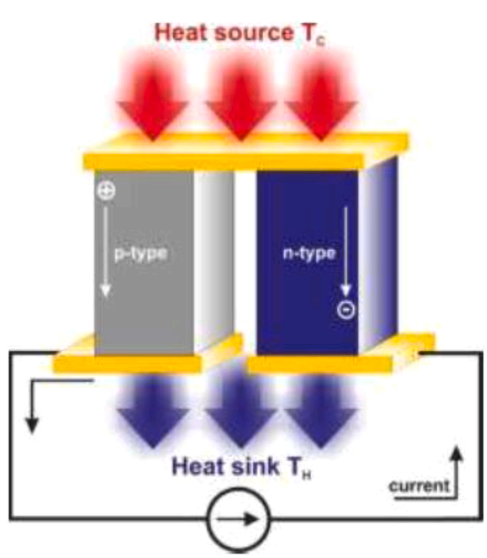

Fig. 4. Working principle of TEG [107].

Fig. 5. Granite rock insulated cookstove [70].

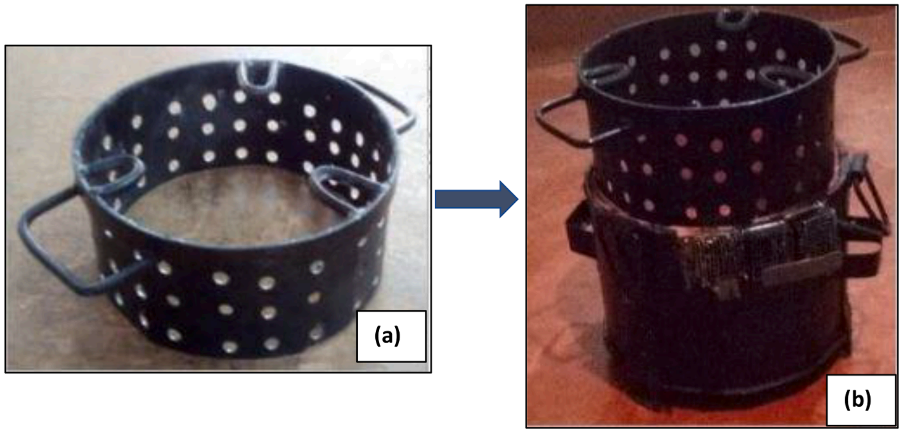

Fig. 6. Modified cookstove for space heating [46].

5.1. Factors limiting improved cookstoves adoption

a *Users' willingness to pay for a new technology*

One major factor limiting the adoption of improved biomass cookstoves is the users' willingness to pay for the cookstoves. This may be associated with some social or behavioral factor in which some set of people believed that if a technology is not free, then they won't put their money into it. In a survey conducted by [112], it was reported that out of 105 surveyed households, only 12 indicated their willingness to pay for an improved cookstove, while only a single household was found to have purchased it after a follow-up survey. However, several studies including [113,114] believed that users' willingness to pay for improved cookstoves is largely dependent on household income and the country's GDP per capita or economic viability. This is because the cost of improved cookstoves is higher compared to traditional cookstoves, which are most often built at no cost by most households. Thus, financial aid is required to reduce production costs and make the products affordable to consumers [73]. On this basis, it will be difficult for low-income households to purchase or pay for improved cookstoves, also it will be difficult for a country with low GDP per capita to establish a fully commercialized market for improved cookstoves, which consequently limits adoption.

Based on this, more interventions that will provide free cookstoves are required in scaling up adoption or more importantly, policies that will compel usage should be put in place. While the aforementioned pathways are taking place, they seem to be at a slow pace. Hence, the level at which the target users are sensitized to the harmful effect of traditional cookstoves plays an enormous role and may change the narrative. Thus, enlightenment and sensitization campaigns are equally essential.

a *Low income and cost of improved cookstoves*

Contrary to the previous point, some households are willing to purchase cookstoves but could not due to the market cost. While it is important to ensure large-scale production, it is equally essential to ensure that the cookstoves are subsidized or affordable to the target users. In a survey conducted by [115], it was observed that the inability of households to purchase improved cookstoves due to cost is one of the major barriers limiting adoption. Low income was observed to be a major determining factor in the adoption of improved cookstoves [115, 116]. On this basis, [117] believed that to scale up adoption, income-generating activities or projects must be put in place to improve household income. In addition to the inability to purchase the cookstoves, some households that owned improved cookstoves find it difficult to maintain them for lack of money for repairs and maintenance [111]. To curb this, [118] reported how government intervention such as subsidy policies significantly aided the adoption of improved biomass cookstoves in Nepal. In the same vein, [109] observed that by subsidizing the cost of cookstoves in rural Rajasthan, adoption improved [109].

a *Unavailability of improved cookstoves in local markets*

The unavailability of improved cookstoves in local markets has been a deterring factor to adoption. Though there are households interested in improved cookstoves, [72] observed that the stoves are not available in local markets. To achieve a wide-scale adoption, there is a need to develop a thriving global market for improved cookstoves and fuels, with the capacity to sell tens of millions of clean cookstoves annually [119]. Without such provision, it will be difficult to effectively and sustainably address the enormous cooking needs of more than 600-800 million households globally that still use solid fuels in traditional cookstoves [120].

a *Non-involvement of end users in decisions relating to the design and development of improved cookstoves*

Improved cookstove promotion and dissemination programs tend to focus more on technology rather than end-user preference [71]. As a result, the adoption has been very slow [115]. Therefore, a lot of improved cookstoves proven to be efficient are still far from being accepted by people [58]. It is worth noting that by not involving the end-users in the design, and fabrication, as well as training on the use and maintenance of improved cookstoves, acceptability, and adoption will keep slowing down. This even goes beyond cookstoves to other energy technology [121]. It was noted that dissemination approach such as training of end-users affects the rate of improved cookstove adoption [122]. By involving the end-users, it shows that their preference is respected and will be considered, and therefore the designers, manufacturers, or those bringing in the intervention will be intimated with the specific form or type of improved cookstove designs that will be more acceptable to a specific set of people based on some social, economic or cultural factors. On this note, [78] observed that double-pot designs were more acceptable in India than single-pot designs. Another drawback of not involving end-users is that their intrinsic values and ethics will not be considered in building the cookstoves [13].

5.2. Potential factors that will enhance the adoption of improved cookstoves

a *Development of low-cost models*

Table 4
Some recent advances in cookstove research.

Study description	Description/ Potential Benefits	Remark	Refs.
Electricity generation from cookstoves	• The excess heat generated in cookstoves is harnessed and converted into electricity with the aid of a thermoelectric generator (TEG). • The heat generated is used to power a small D.C fan that supplies air to the cookstove and to charge mobile phones, power small radios, and LED lamps	• The idea of TEG is timely and would go a long way especially if the energy capacity could be improved	[96, 46,97, 46]
Emission reduction using a Jet-flame forced draft retrofit accessory	• This technology was developed to curtail toxic gas emissions and fuel consumption in biomass cookstoves. • It operates by simply placing the device beneath the fuel bed of the cookstove to eject air into the combustion chamber. • The device has the potential to curtail PM and CO by 89% and 74% on average relative to the natural draft models	• It is important to calibrate the device by evaluating it in different environments to come up with average air speed per ambient condition, stove, and fuel type	[103]
Cookstove emission control using Internet of Things (IoT) enabled devices	• Seven air pollution control algorithms were developed. The algorithms were linked to IoT sensors and IoT-enabled stove hoods, portable air cleaners (PAC), and bathroom exhaust, all connected to a circuit monitor for tracking the cookstove's operation. • The technique was found to minimize integrated $PM_{2.5}$ concentration by 81% to 94%.	• Having stated the features of IoT sensors and IoT-enabled stove hoods, and portable air cleaners (PAC). Feature studies may explore the possibilities of incorporating the air cleaner and hood as a component of the cookstove to curtail the emission of toxic gases	[98]
Use of Sensors to monitor fuel consumption, air quality, and adoption	• The use of sensors provides more accurate performance metrics compared to manual estimation.	• While the technology provides a more accurate measure, it is important to evaluate it under different conditions	[104, 105]
The use of biomass briquettes and pellets to power cookstoves	• This involves densifying bio-waste into solid fuels to minimize the intense use of charcoal and fuelwood which has significantly contributed to deforestation, especially in Africa where over 80% of the population relies on solid fuel.	• Studies have shown that most lignocellulosic biomass materials have neutral to zero emissions. This indicates that densified biomass such as briquettes and pellets have the potential to improve the health of its users.	[54, 99]
Battery-supported eCooking approach	• A solar hybrid mini-grid battery support system was developed to support electric cooking in the absence of national grid power. • This is an emerging approach believed to address the global challenge of biomass cooking such as pollution, frequent purchase of fuel, etc.	• A good system to augment electric cookstoves. However, the cost and durability of the battery is imperative. Hence, may not be suitable for traditional cookstove users	[100]
Hybrid Solar-Biomass Cook Stove	• This hybrid prototype combines the effect of solar and biomass in cooking. • It consists of solar reflectors that trap heat from the sun, thereby improving the thermal performance of the stove and reducing fuel consumption. A 5% increase in thermal efficiency was achieved.	• An improvement to this prototype may involve the addition of reflectors to make the stove fully operational on solar in the daytime and fully operational on biomass in the absence of sun or at night.	[94]
Two-chamber fuel biomass cookstove	• The cookstove is a pyrolysis biomass cookstove with two separate chambers (one for combustion and one for pyrolysis). • The cookstove uses different biomass fuels at a similar pace as it is insensitive to fuel type. It produces heat and nitrogen- and carbon-enriched biochar which can be used as a soil amendment.	• This concept is very vital and possesses the potential to cut down the cost incurred in fuel and fertilizer purchase	[106]
Incorporation of perforated rolled steel sheets in cookstoves to enhance space heating capacity	• This concept involves rolling and perforating a steel sheet (Fig. 6a) and placing it on top of a cookstove (Fig. 6b) for heat emission. The emitted heat is then utilized for space heating	• A low-cost technique of space heating. Thus, has the potential of bridging the gap associated with the cost of modern heating devices	[46]
Granite rock insulated cookstove	• Granite rock (a high-density rock with good thermal properties) has been discovered as a good insulation material. • While this can be used alone, Bantu et al (2018) used it alongside fiberglass and air insulation concealed in a stainless steel cladding (Fig. 5) to	• While the authors have evaluated the granite rock along with other materials. It is believed that the rock alone is sufficient to provide good insulation	[70]

(continued on next page)

Table 4 (*continued*)

Study description	Description/ Potential Benefits	Remark	Refs.
	improve the cookstove's thermal performance. • The technology has the potential for reducing fuel use by over 78% compared with the traditional open-fire stove.		

As the cost has been pointed out as one of the major factors limiting the adoption of improved cookstoves, researchers and manufacturers need to focus on building low-cost but efficient models. Based on this, a low-cost technique called rock-bed was developed [123]. This is a modification to the open fires which saves about 30% of the fuel and reduced emissions by roughly 0.48 tons of CO_2e per user per annum compared to the traditional open fires. Similarly, [74] incorporated a twisted tape assembly in an existing traditional cookstove and observed a fuel saving of 21%, a reduction in cooking time by 18.5%, and an emission reduction of 38%. On the same premise, the whirl concept was developed by [95] as a way of improving combustion and emission performance. The concept involved incorporating a metallic mesh within the combustion chamber. Although the concept has not yet been evaluated in traditional cookstoves, it was found to improve thermodynamic efficiency by 13 % when compared with a rocket stove. Thus, these low-lost technologies can be improved further and commercialized. However, it is still more important to have the advanced models downscaled to minimize cost.

a *Making processed biomass fuels available and affordable at local markets*

One of the ideas behind the development of improved cookstoves is to minimize emissions from traditional cookstoves which are mostly powered by charcoal and fuelwood. On this basis, most of the improved cookstove models are designed to use processed biomass fuels such as briquettes and pellets that are emission neutral, as studies have shown that they are cleaner than charcoal and fuelwood. However, these fuels are not commercially available in most countries. It is believed that with such an idea, improved cookstoves will attract more interest, especially from those that are conscious of the environment. In this medium, the government, policymakers, and intervention bodies will be interested and may invest in large-scale production and dissemination.

a *Enhancing global interventions and cookstove projects*

To address the various drawbacks associated with traditional cookstoves, there is a need to promote and disseminate improved cookstoves [108,123]. This can be achieved through interventions and support from different actors such as governments, the development community as well as national and global financial institutions [109]. These interventions will not only enhance accessibility but will significantly improve the overall public health of its users [124–127]. On this basis, the provision of improved cookstoves for free was observed to have boosted adoption in Ghana [72]. In the same vein, improved cookstove promotion intervention has reportedly enhanced adoption in rural Rajasthan, with about 45% of the sample households adopting within the early stage of intervention [109]. Hence, incorporating clean cooking programs into other major intervention programs will aid in ensuring global access to clean household energy [128].

Albeit, there are a plethora of cookstove intervention programs implemented by different institutions, Non-Governmental Organizations (NGOs), international organizations, and government and private initiatives [21], such as the Global Alliance for Clean Cookstoves (GACC) which is one of the commonest aimed at achieving improved cookstove adoption by 100 million homes by 2020 [129], there is need to spring up these interventions to go far and wide. Through such interventions, it was estimated that the global technical potential for minimizing GHG emissions through improved cookstoves stands at 1 gigaton of carbon dioxide (1 Gt CO_2) per year, based on 1 to 3 tons of CO_2 equivalent per stove [130].

a *Setting up policies on the use of improved cookstoves*

Government policies are very pertinent in promoting the adoption and dissemination of improved cookstoves. With this, apart from establishing policies that will regulate the cost of cookstoves to ensure it is within an affordable range for low-income households, [122] believed that adapting measures that will reduce the cost of dissemination is equally important. Furthermore, since women are the major end users, policies that will ensure women's participation in decision-making and/or policy formulations regarding improved cookstoves will scale up adoption and dissemination [131]. Another perspective that may scale up dissemination involves setting up cookstoves dissemination programs and ensuring adequate training of participants [122]. Furthermore, government policies on other energy options such as electricity and gas must be reduced to emphatically capture the use of improved cookstoves [108]. This is essential as users of traditional

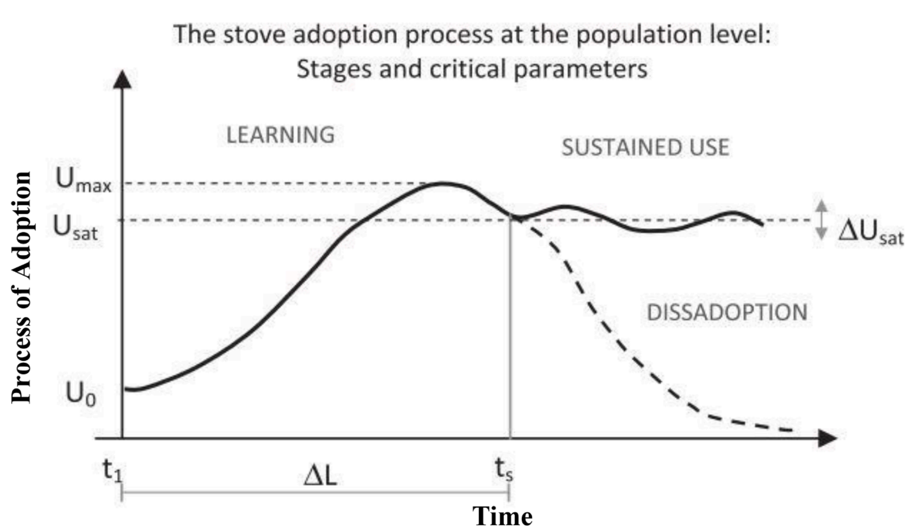

Fig. 7. The adoption process of cookstoves at the population level: stages and critical parameters. Modified from [110].

cookstoves are major residents of rural and peri-urban parts where electricity and gas might not be available or may be unaffordable as an option.

6. Conclusion

The paper successfully reviewed the literature on the technical aspects of biomass cookstoves including the recent advances. This is critical especially as the number of solid fuel users is increasing globally. Overall, the following conclusions were drawn from the present review:

- Solid bio-fuels like briquettes and pellets have the potential to sustainably replace conventional solid fuels (fuelwood, charcoal, and coal) in powering improved cookstoves. Apart from being an alternative energy source, it is an effective measure of reducing deforestation and mitigating climate change.
- Although emissions from cooking do not significantly contribute to atmospheric greenhouse gas emissions, when combined with the impact of forest degradation especially as the forest plays a vital role in carbon sequestration, it then becomes of utmost concern. Thus, solutions and remedies that include the use of improved cookstoves and biofuels are imperative as they have demonstrated good performance in fuel use reduction which invariably curtails deforestation.
- In addition to establishing markets for improved cookstoves and ensuring that the prices are affordable to low-income earners, the rate of adoption and dissemination would significantly improve if end users especially women are involved in decision-making and policy formulation regarding the development and use of improved cookstoves.

7. Recommendations for future investigation

The present review found gaps in the literature and recommends thus:

- Although improved cookstoves have shown promising features, it is important to broaden research in the aspect of models that operates similarly to traditional cookstoves to ease the adoption process. This would be of great impact, especially in Africa where studies have shown a higher preference for traditional models and unwillingness to switch to improved models. Thus, emphasis should be on simple natural draft models made of locally available materials than the force draft models.
- Several improved cookstoves have been developed across the globe. However, the slow rate of adoption has been a major concern in the cookstove sector. Thus, it is essential to further research novel approaches that will scale up dissemination and boost the adoption of improved cookstoves. Achieving this would enhance fuel saving which translates to deforestation control and cost saving, and minimize indoor air pollution, especially in Africa where a large percentage of the population still cook with harmful fuels and traditional cookstoves.
- The environmental and health impacts of burning raw biomass, coal, charcoal, and fuelwood are enormous. Future models should be focused on the use of solid bio-fuels like pellets and briquettes or liquid bio-fuels. This is highly imperative, especially in regions where lignocellulosic biomass is largely available but underutilized.
- There is a need to incorporate environmental and social factors in the research and development phase. This may include designing cookstoves based on peculiarities like cultural beliefs and traditions of the target environment and people. With this, end users' perceptions are also imperative. This will improve research and development, as well as the adoption of improved cookstoves.

CRediT authorship contribution statement

S.U. Yunusa: Conceptualization, Writing – original draft. **E. Mensah:** Supervision, Writing – review & editing. **K. Preko:** Writing – review & editing, Supervision. **S. Narra:** Supervision, Writing – review & editing. **A. Saleh:** Supervision, Writing – review & editing. **Safietou Sanfo:** Supervision. **M. Isiaka:** Conceptualization. **I.B. Dalha:** Writing – review & editing. **M. Abdulsalam:** Writing – review & editing.

Declaration of Competing Interest

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

Data availability

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

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