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Review article

Recent developments and challenges in biomass cookstove

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ABSTRACT

The growing demand for more efficient cooking methods has been fueled by the rapid advancements in biomass utilization. Considerable progress has been made in the development of a biomass cookstove that is both highly thermally efficient and produces less pollution. This review provides a comprehensive overview of the current status and advancements in biomass cookstove technologies. It explores various types of biomass cookstoves, with a particular focus on advanced models available in the market. The paper explores the recent advancements, highlighting the effectiveness of ceramic materials in combustion chambers for reducing emissions, and the impact of introducing swirl vanes and hybrid air injection systems on fuel consumption and overall performance. The review also discusses the important design strategies and limitations that affect the efficiency of these cookstoves. In addition, it acknowledges the considerable challenges in the field, such as design limitations, maintenance, and performance testing variations. Given recent advancements in biomass cookstove technologies, this review identifies important areas for future research. Although there have been significant research in the field of biomass cookstove, there are still gaps in the literature, particularly when it comes to complex heat transfer mechanism. These gaps in knowledge emphasize the need for further investigation to develop more practical and efficient cooking technologies.

1. Introduction

As the world recovers from the economic crisis and recession, the global demand for energy is expected to increase in next decades (Gardner, 2015). Currently in the global energy market natural gas, petroleum oil and coal are the primary source of energy. These primary sources are finite resource that takes millions of years to form within the Earth. Consequently, their reserves are limited and prone to depletion as they are consumed. Biomass is the sole additional naturally existing resource that contains energy-rich carbon and possesses adequate potential to serve as a substitute for these primary fuels (Balat and Ayar, 2005). Currently, around 2700 million people in developing nations depends on the use of biomass such as animal waste, agriculture waste and charcoal for their cooking and heating. The dependence on biomass as a primary fuel for cooking is high in regions of Sub-Saharan Africa and South Asia, with a significant percentage of the population relying on this energy source (Tanaka et al., 2010). In Sub-Saharan African countries, biomass accounts for approximately 75 % of the total energy

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consumption (Abebaw, 2007). In rural areas of these developing countries, traditional biomass is the most common source of energy consumption, accounting for over 90 % of the total energy used (Birol, 2009). Although in urban areas, where it is assumed that alternative sources of energy are available, many people still prefer to cook their food using traditional methods that involve fuels such as wood or charcoal (Karekezi and Majoro, 2002).

In recent years, the concept of "clean cooking" has received increased attention in both research and policies, and it has served as a foundation for a variety of international projects (Putti et al., 2015). In the past, people used the traditional approach of cooking, which is basically the Use an open fire comprised of biomass fuel, sometimes with a shield wall of bricks or mud used to support cooking pots and pans and act as a wind or air barrier (Karekezi and Majoro, 2002). The three categories of cooking technologies that exist include traditional, improved and advanced cookstoves which are based on their efficiency. Biomass is burned in traditional stoves or stoves with a three-stone configuration to cook food in many developing countries. The heat energy produced during biomass combustion is only 5–10 % consumable, making these cooking stoves significantly inefficient and emitting high pollutant emissions (Clark et al., 2010, 2009; Ram et al., 1984). Improved cookstoves are the second category, and they have the potential to lower the health hazards that are related with cooking. The fact that improved biomass stoves don't always function well enough to provide appreciable health advantages over traditional stoves is a major issue. The last one, or the which is also known as the next generation cooking technology is advanced cookstoves (Kshirsagar and Kalamkar, 2014). This technology focuses on the improvement of complete combustion of biomass and thus the thermal and performance efficiency of over 40–50 % can be easily achieved. This has many advantages compared to other technologies used. Therefore, it has potential opportunities for further development and applications (Kshirsagar and Kalamkar, 2014).

The adoption of biomass cookstoves is a significant step towards sustainable and efficient energy use, particularly in developing countries. The design of these cookstoves allows them to burn biomass fuel sources like wood, crop residues, and animal dung more efficiently and with lower emissions (B. Sutar, 2022). The following factors influence the adoption of these enhanced cook stoves: The convenience of a particular cooking device plays a crucial role in determining its usage and overall acceptance. Households are more likely to embrace biomass cookstoves that are user-friendly and require minimal maintenance due to their practicality. Additionally, the presence of high-energy fuels such as pellets and briquettes has played a role in promoting the use of biomass cookstoves. Technological advancements have identified these fuels as cleaner and less smoky than conventional biomass fuels (Wamalwa et al., 2022). Another aspect of the adoption of cookstoves is the ease and efficiency of preparing local meals, which may require less cooking time. If usage patterns closely match a population's traditional cooking and eating habits, then the possibility of adopting the cook stove increases. One of the reasons behind the surge in biomass cookstove demand was the affordable prices of these cookstoves, which can be further improved by obtaining a loan to fund the purchase of the cookstoves (Jeuland et al., 2020).

However, there has been an increase in the use of biomass as a fuel for cooking, leading to heightened concerns regarding its impact on both the environment and human well-being (Zhu et al., 2024a). As per WHO report, it has been determined that the pollution emitted from burning biomass is responsible for approximately 3 % of the overall global health disorders. This pollution is the main cause of 1.6 million unexpected deaths each year, with 0.9 million of these causalities occurring among children under age of five (Organization, 2002). Stoves with improved efficiency at burning biomass have been manufactured and given to an estimated 53 million households since 2010 (Ruiz-Mercado et al., 2011). Observational studied and experiments reveal that many programs failed to successfully replace the outdated biomass stoves with new designs that performed well in community and significantly reduced air pollution (Karekezi and Majoro, 2002; Kshirsagar and Kalamkar, 2014; Rehfuess et al., 2014). The negative environmental and human health effects of traditional cooking stoves have prompted the development of more advanced design, safe, and clean efficient biomass cooking stoves.

In view of the above, society has been obligated to develop innovative cooking methods that are both environmentally friendly and technologically advanced to reduce emissions and balance energy demands. It has recently come to light that the most effective strategy for achieving the multiple objectives of improving fuel efficiency, securing public health, mitigating negative effects on the climate, and cutting down on pollutants is to shift toward more advanced cooking technologies that have a high combustion efficiency and a low emission rate, and do not cause any considerable pollution in the initial place. Now such biomass cookstoves are available that produce less emissions and are more efficient than traditional stoves in laboratory testing, apparently possible with more advance features. These recent biomass cookstoves rely on electric fans to supply the forced air necessary for cooking. Biomass cookstoves that use forced air can increase the combustion of biomass and greatly cut down on hazardous emissions if they are designed correctly (Jetter et al., 2012; Rapp et al., 2016; Just et al., 2013; MacCarty et al., 2010). In the course of the last several decades, there has been significant progress in the field of technologies pertaining to cook stoves. In recent years, research has been actively being conducted in this sector by academic institutions, industries, and research centers. Several techniques have been used by researchers to improve cookstove's efficiency like the use of thermoelectric generators, production of high-quality biomass pellets, increasing the number of reactors in the stove combustion chamber and improving the air supply for complete combustion of biomass in the stove.

Certain challenges lie in the development of an efficient advanced cookstove to make a material difference. Some issues raised related to differences in emission measurement in the lab and field have been under research even after the issue was first realized, due to the complex nature of these issues. There are some other limitations regarding stove repair, pellet manufacturing, and proper operation of biomass cooking technologies. Therefore, it is necessary to enhance the efficiency and working phenomenon of biomass cookstoves to mitigate pollutant emissions to bring a more significant impact on the lives of developing countries.

This review article presents a thorough analysis of various cookstove technologies that have been adopted globally. The paper provides a comprehensive review of the latest designs of biomass cookstoves, including both the traditional and advanced models. These different types of stoves are further elaborated upon in detail. Furthermore, it highlights the latest advancements in biomass cook stoves, the modern approach to designing these stoves, the specific technical details that define them, and the challenges associated with this rapidly growing field of technology. The review also highlights areas which require further research and development for biomass cookstove technologies, providing the reader with valuable background information on current and potential future advancements in this crucial field.

2. Classification of biomass cookstoves

The biomass cookstove classification is most important to meet user choices according to locally available resources. Due to its unique design for the characteristics of the fuel, a single cookstove cannot work similarly while using several biomass fuels for cooking. The woody biomass, agricultural residues, charcoal, dung cake, leafy biomass, sawdust etc. are used as a fuel for a biomass cookstove (B. Sutar, 2022; Organization, 2002). Therefore, cookstoves are separately designed as per the locally available biomasses and energy needs of a family (Ram et al., 1984). Moreover, the development of multi-fuel cookstoves should be stressed because of biomass diversity in local areas rather than biomass cookstove. The biomass cookstove classified on base of material, portability, design, and application. Fig. 1 presents a graphical representation

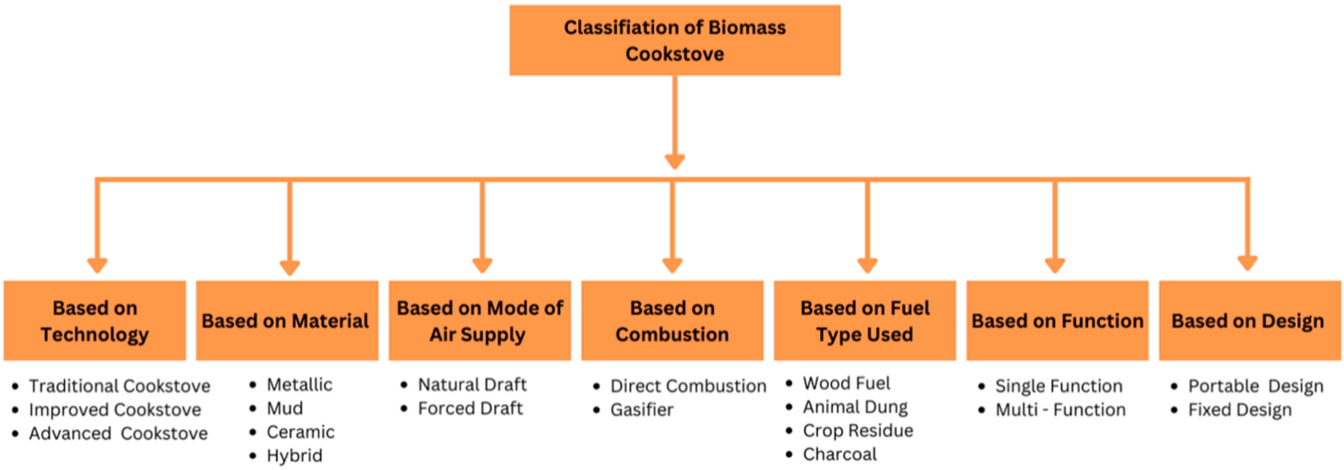

Fig. 1. Classification of biomass cookstoves.

showing the different categories of biomass cookstoves.

2.1. Technological advancements in biomass cookstoves

2.1.1. Traditional cookstoves

Traditional stoves have changed throughout history based on society's food practices and how their culture worked. These stoves are the least expensive, and people who use them know how to use them, so they are widely used. There are two kinds of traditional stoves. The first is the "three-stone fire" that consists of a fire built with three stones on the ground and a cooking pot placed on it. The three-stone fire stove's main flaw is that it doesn't work very well. Three-stone fire stoves take a moderate amount of time to boil, use a lot of fuel and release considerable amounts of carbon monoxide (CO) and particulate matter (PM) while having a marginally lower efficiency of up to 20 % (Jetter, 2009; Still et al., 2011). Aside from this, three-stone fire stoves are the least safe because they leave the fire out in the open (Still et al., 2011).

The "Built-in stove" or "Mud-stove" is the second kind of traditional stove. The modified stove is based on the three-stone fire stove design. The concept of a "Built-in Stove" refers to a mud-based design that is mostly permanent and keeps fire from going anywhere but down into the ground. Built-in stoves have some upper hand over three-stone fires: the fire is enclosed, so less radiation is lost; only a small amount of fuel can be added at a time, so less fuel is used; and the gas path is enclosed, so less air from the room is pulled in. But if insufficient air is supplied to the fuel, it can result in incomplete combustion. The presence of certain factors can contribute to the increased pollution of indoor air. The results of laboratory experiments conducted on mud stoves indicate that these stoves can rapidly boil water. However, it was observed that they also emit a significant amount of carbon monoxide and particulate matter. Furthermore, the efficiency of mud stoves in terms of heat utilization was found to be approximately 29 %. Despite these drawbacks, it is worth noting that mud stoves offer a certain level of safety due to the containment of the fire within their structure (Still et al., 2011).

2.1.2. Improved biomass cookstoves

Improved biomass cookstoves are designed with the intention of improving the cookstove combustion system to increase its thermal efficiency and reduce pollutant emissions. The goal of an improved cookstove design is to fix what's wrong with traditional stoves while keeping costs down and making them easy to use. Several improved design methods have been introduced to improve their performance, such as the placement of a grate under the combustion zone, low density surrounding walls, the adjustment of a small chimney inside the cookstove body, the use of the right insulation, and the design of the cookstove pot support to transport maximum heat to cooking potions. Currently, there are improved biomass cookstoves available in the market that possess thermal efficiency up to 30 % (Jetter, 2009; Still et al., 2011), cut out pollutant emissions between 40 % and 75 % (MacCarty et al., 2008). In recent years, there has been a growing interest in exploring the use of novel materials for constructing improved biomass cookstoves. Rocket stoves and gasifier stoves are widely recognized as the most prominent categories of improved cookstoves.

2.1.3. Advanced biomass cookstoves

Advanced biomass cookstoves that were made recently are based on more technical research and usually cost more. These cookstoves are made with better technology and design, like grates, insulation, forced airflow, and more durable materials, so they burn biomass cleaner and are more efficient (Kumar et al., 2013). Advance biomass cookstove can be made in a factory and goes through a lot of quality testing, which makes it more likely that all the stoves will have the same design. Even though the current ABS shows that emissions are much lower than with traditional stoves, they are still not as low as with LPG. Now, there exits two primary types of advanced biomass cookstoves: gasifier stoves that burn fuel in two stages and improved "Rocket" stoves that burn fuel in only one stage. "Oorja" and "Philips" stoves are both Gasifier type advanced biomass cookstoves models (Jetter et al., 2012; Mukhopadhyay et al., 2012).

2.2. Material advancements in biomass cookstoves

2.2.1. Metallic stoves

These metallic cookstoves are built from materials like steel, metal or other heavy metallics like cast iron etc. Metallic stoves are easy to move, light, heat up quickly, last a long time, and don't need much maintenance. They come in many different styles and colors. Traditional biomass cookstoves are commonly built using materials such as concrete, pottery clay, and bricks. Although, due to less weight and other performance-enhancing properties such as low thermal inertia, improved biomass cookstoves are designed using metal materials (Sutar et al., 2015). Metals are used for current stoves noted for their high performance, and some of them include ceramic linings inside to extend their longevity in high-temperature conditions. Due to its light weight, a metal stove body stores less energy, but it can lose more heat because metal is a better conductor of heat than other materials. The cons are that they tend to rust, can cause burns, and are the most expensive (Kshirsagar and Kalamkar, 2014).

2.2.2. Mud stoves

Mud stoves are constructed from locally sourced organic materials such as sand, silicate materials, clay, and other mixers of clay with straw or sawdust. Most frequently, the combination is composed of dung to increase stickiness, an organic binding substance, and clay or dirt. Traditional and improved cookstoves can look different in different places because of the materials used, the number of potholes, the use of a chimney, and other things. Most of the earliest stoves that came from the Indian subcontinent were made of mud. After the three-stone fire stove, the mud stove is the most inexpensive stove you can buy. Mud stoves, on the other hand, can be damaged by insects, weather, and putting too much fuel in them. Because of this, they need more maintenance and usually only last one to two years (Kishore and Ramana, 2002).

2.2.3. Ceramic stoves

Ceramic stoves are constructed using a variety of materials, including mica, sand, clay, and other similar substances, along with chemical additives to reinforce the ceramic. Mud stoves and ceramic stoves are distinguished from one another by the fact that ceramic stoves are heated to a high temperature in a kiln, a process that results in the ceramic stoves having a superior finish as well as improved insulation and a longer lifespan. To safeguard the ceramic body, every ceramic stove manufactured in the present era has a metal casing surrounding it. A ceramic stove, provided it is properly lighted, is more long-lasting than a mud stove. However, in comparison to mud stoves, ceramic stoves are both more expensive and difficult to construct. In addition to this, they need to be maintained, and they are not compatible with all sizes of pots (Kshirsagar and Kalamkar, 2014).

2.2.4. Hybrid stoves

Nowadays, biomass cookstoves are built from a diverse range of materials, including ceramic, metallic materials, concrete, and mud mixtures. Most improved and advanced biomass stoves are designed as hybrid cooking stoves. This means that the combustion chamber, where the fire burns, is crafted from ceramic to enhance heat retention, and improve combustion efficiency. Meanwhile, the remaining parts of the stove are typically constructed from metal, ensuring durability and effective heat transfer (Kshirsagar and Kalamkar, 2014).

2.3. Air supplying configurations in biomass cookstoves

2.3.1. Natural draft stoves

Almost all the first stoves for cooking at home were based on free convection. Even now, free-convective stoves are hard to avoid because they are easy to make and can be bought for a low price. Natural-draft cookstoves are a type of biomass stove that pulls air from the area around it through free convection and doesn't need an air supply from the outside. Because it doesn't have a fan, a natural-draft stove can't mix the gases that can catch fire better (Kumar et al., 2013). In a biomass stove with free draught, the fuel burns around the solid fuel, which leads to incomplete combustion, which raises the emissions (Kar et al., 2012).

2.3.2. Forced draft stoves

If fans are used to bring air into a biomass stove so that it can burn, the stove is called a forced-draft stove. Stoves with forced draught or fans are some of the most promising. Cookstoves that include fans have been found to have multiple benefits, including the reduction of pollution due to their improved fuel combustion efficiency. Additionally, these cookstoves enhance the transfer of heat to the cooking pot, further enhancing their overall performance. At first, these stoves were too expensive for most people to buy. This was partly because the fan and the electricity needed to run it were so expensive. But these problems were solved by the relatively low cost of computer-based fans and the use of the thermoelectric generator. It has been studied that forced-draught stoves use on average 37 % less fuel than natural-draught stoves. They also put out 80 % less CO and almost no PM (Still et al., 2011).

2.3.3. Hybrid draft stoves

Hybrid draft biomass cookstoves are designed in such a way by combining the principles of both natural draft and forced draft stoves (Modi and Upadhyay, 2021). These cookstoves have several air draft combinations; the most promising type of hybrid biomass cookstove is the use of fan air for either primary or secondary air inlets with a combination of natural air supply (Ghiwe et al., 2023). These biomass cookstoves offer more performance than traditional biomass cookstoves available on the market but use less energy to work as compared to forced draft biomass cookstoves. There are biomass cookstoves that use natural draft for primary air supply and forced draft for secondary. Hybrid draft stoves may have limitations in terms of design as these stoves have less control over the flame temperature and distribution as half of the process is handled by natural air supply. The design of these stoves is somehow similar to that of traditional stoves in that it adjusts natural air for the combustion process along with forced air.

2.4. Combustion mechanisms in biomass cookstoves

The process of burning fuel with air to liberate the chemical energy that is held in the fuel is referred to as combustion (Kshirsagar and Kalamkar, 2014). The combustion process significantly influences both the design and functionality of a cookstove. The combustion of solid fuel is more complex compared to the burning of liquid or gaseous fuel due to the various processes involved in pyrolysis and gasification (Kumar et al., 2013).

2.4.1. Direct combustion cookstove

Most of the stoves are of the direct-combustion kind, which directly convert biomass into chemical energy (Kshirsagar and Kalamkar, 2014). Combustion cookstoves involve the burning of solid biomass fuel in a chamber containing primary and secondary air, the sum of which is greater than the stoichiometric quantity of air required for combustion. The combustion of solid biomass fuel leads to the generation of various heated byproducts. These include the heating and drying of the fuel, the pyrolysis of the fuel, which releases volatile substances and produces char, the combustion of the volatiles through flames, and the combustion of the char through smoldering (Sutar et al., 2015).

2.4.2. Semi-gasifier cookstove

"Gasifier cookstoves" are stoves that turn the biomass into gas before they burn it. Biomass gasification is becoming more popular in new designs because it is usually a cleaner way to burn fuel than combustion stoves. The process of converting biomass into a combustible gas by utilizing heat and chemistry is known as biomass gasification. Like combustion stoves, biomass undergoes pyrolysis at high temperatures, losing its water and decomposing into char and volatiles. Only a small portion of the volatile matter and char in gasifier stoves get oxidised because the oxygen content is kept low. At high temperatures, the created carbon dioxide and water vapour flow over the residual char, where they are transformed into carbon monoxide and hydrogen. "Product gas" is the name given to the produced gaseous fuel. Gasifier stoves can be classified as top-lit updraft, crossdraft, or downdraft depending on the direction of air flow into the appliance. A constant, even flame that is simple to control, very low emissions, excellent efficiency (between 35 and 50 percent), and reduced maintenance are just a few advantages of gasifier stoves. Most gasifier stoves available today are forced-draft models (Mukunda et al., 2010; Reed et al., 2000; Hegarty, 2006).

2.5. Fuel types used in biomass cookstoves

Wood fuel cookstove: The primary source of energy in the majority of residential areas in developing nations is wood fuel (Yevich and Logan, 2003). Most modern stoves use wood as their main fuel source.

Cattle manure cookstove: In many developing nations, such as India, cow dung serves as an essential cooking fuel. It is commonly utilized in conjunction with other fuel sources, including agricultural waste and wood fuel (Mukunda et al., 2010; Lambe F, 2012). This is because many regions of the country do not have sufficient access to wood, therefore residents instead use animal manure as a fuel source for their stoves.

Crop residue cookstove: In places where there is a severe lack of wood fuel, crop waste is an important way to cook. Crop residue refers to the remaining plant materials, including straws, leaves, pods, husks, cobs and shells, that are left behind after the harvesting process.

Charcoal cookstove: Many people who live in cities in underdeveloped countries cook their food with charcoal as their primary source. Most people in the eastern and northern parts of the continent use charcoal as a home fuel (Yevich and Logan, 2003; Mwampamba, 2007). Africa is responsible for producing approximately 50 % of the global charcoal supply. Charcoal is widely used as a heating source in various regions across the globe, including Thailand in Asia. However, it is important to note that the majority of households in Latin America do not rely on charcoal as their primary fuel source (Yevich and Logan, 2003).

2.6. Based on Cookstove Functions

Single function cookstove: Cooking, heating water or the surrounding area, smoking fish or meat, baking, milk simmering, grain or flour roasting, and other activities of a similar nature can all be accomplished with a single-function stove. Most of the ranges only have a single cooking function.

Multiple functions cookstove: In addition to their use for cooking, multi-function stoves can be put to a variety of other tasks, such as the heating of water and spaces, winter heat supply, creation of other useful fuel residues such as char. All these tasks can be accomplished with the multi-function stove. A modern stove with a thermoelectric generator can do more than just cook. It can also provide light and power for electronic devices (Champier et al., 2011).

2.7. Design configurations in biomass cookstoves

2.7.1. Portable design cookstoves

Cookstoves made of metal or ceramic and suitable for use indoors or outdoors are portable. In many warm developing countries, it is common practice to cook indoors during the winter season in order to maintain a warm temperature within the house. Conversely, during the summer months, cooking is often carried out outdoors to minimize the additional heat generated by the stove. The ancient "Uthaao chullah" portable mud burner is the main cooking appliance in Northern India. Gasifiers and "Rocket" stoves are two examples of all-modern ABSs that are portable.

2.7.2. Fixed design cookstoves

Cement or clay are the typical materials used in the construction of fixed stoves. Fixed stoves can involve a wide range, but common examples are multi-pot stoves and mud stoves. Stoves like these are often difficult to move, making them ideal for use by households in developing countries who do not migrate frequently. The number of potholes is used to further categories fixed stoves into one of three categories: single pothole, double pothole, or triple pothole. Table contains popular acronyms based on the classification defined for the biomass cookstoves. Table 1

Table 1
Classification of biomass cookstoves, and relevant acronyms used for the biomass cookstoves.

Classification of biomass cookstoves	Further types	Popular acronyms	References
Technology used	Traditional stove Improved cookstove Advanced biomass cookstove	Chullah, Mogogo, Plancha	(Mukhopadhyay et al., 2012)
Material of construction	Metallic stove	Bukhari, Magh Stove, Matelic Jiko	(Jetter, 2009; Lambe F, 2012; Rahman, 2015)
	Mud stove	Anagi, Rocket mud stove, Astra, Parvati	(Rahman, 2015; Clough, 2012; Barnes et al., 2012)
	Ceramic stove	Gyapa, New lao stove, Ceramic Jiko	(Still et al., 2011; Clough, 2012)
	Hybrid stove	StoveTec, Oorja, Philips HD 4012	(Jetter, 2009; Mukunda et al., 2010; Household cookstoves, 2011)
Combustion mechanism	Direct combustion	Rocket Stove, Gusto Stove	(Bryden et al., 2005; Witt, 2005)
	Gasifier stove	Philips, Oorja	(Jetter, 2009; Mukunda et al., 2010)
Mode of air supply	Natural draft	Vesto, Karve, Sampada	(Jetter et al., 2012; Rahman, 2015; Roth, 2011)
	Forced draft	Side feed fan stove, Tom Reed Woodgas	(Witt, 2005; MacCarty N, 2010)
Fuel type	Wood stove	6 – Brick Stove, Berkeley Darfur Stove	(Jetter et al., 2012; Jetter, 2009)
	Cattle manure stove	Hara	(Kishore and Ramana, 2002)
	Crop residue stove	Jinqilin CKQ−801, Models 150 & 250	(Jetter et al., 2012; Roth, 2011)
	Charcoal stove	Kenyan Charcoal Jiko, Lakech Stove, Laura Clough	(Jetter et al., 2012; Jetter, 2009; Clough, 2012)
Function	Single function stove		
	Multi-function stove	Model LX Stove, Bukhari	(Rahman, 2015; FAO, 1993)
Design	Fixed stove	Uganda 2-pot, Onil, Ecostove	(Still et al., 2011; Jetter, 2009)
	Portable stove	Uthaao Chullah	(Mukhopadhyay et al., 2012)

3. Commercialized biomass cookstove technologies/systems

The term "advanced biomass cookstoves" refers to more recent versions of cookstoves that are manufactured in accordance with the research and standards used in modern product development and technical innovation. These stoves provide several benefits over traditional ones, including higher levels of durability and safety, as well as lower levels of emissions (Kshirsagar and Kalamkar, 2014).

3.1. IITD model advance cookstove

This advance cookstove is designed and manufactured by Indian Institute of Technology, Delhi. This stove is built of mild steel and is a forced draft cookstove with a cylindrical combustion chamber featuring an arrangement for variable speed fans driven on batteries and may be controlled by the knobs attached with a microcontroller. Axial fans were used to bring in both primary air and secondary air to meet the combustion's need for air. The ratio of the flow rates of primary air to secondary air was changed between 1:3 and 1:5. The fan attached to the base of the cookstove's inner cylinder provides the main source of air. The air is used to convert the biomass pellets into gas by passing them through the grate located at the cookstove base. The inflow of secondary air into the combustion chamber is facilitated by openings located on the upper portion of the combustion chamber. Prior to entering the combustion chamber, the secondary air was heated by passing through the designed space between the cookstove cylinder body. This stove's schematic diagram is shown in fig. The IITD advance cookstove has a thermal efficiency of 41.34 %, which is 2.3 times greater than the efficiency of traditional stoves (Himanshu et al., 2021). The fuel source of choice for the cookstove is either wood or agricultural waste products. According to the Ministry of New and Renewable Energy (MNRE), the Government of India's Advance IITD Cookstove is more efficient in reducing CO and PM. This stove is currently available in India.

3.2. Berkeley air injection cookstove

This advance cookstoves are designed and developed by Lawrence Berkeley National Laboratory. Berkeley air injection cookstove have two primary categories: Berkeley Umbrella Stove (BUS) and Berkeley Shower Stove (BSS). They have air manifold to direct air jet to flame to promote complete combustion and less emission. The Berkeley Umbrella Stove (BUS) is different from other stoves because its BDS (Berkeley Darfur Stove) firebox has air injection manifold with a shape similar to umbrella. In the gas-phase combustion zone, downward-pointing jets help mix the fuel and make sure it burns completely. The Berkeley Shower Stove (BSS) uses a maximum of 8 stainless steel "shower heads" to propel air over the firebox wall and into the gas-phase combustion zone. These "shower heads" can be taken off and switched out. The air injection manifold is located under the grate of the stove. This was done so that the BUS wouldn't act as a shield against radiation. In addition, the stove and manifold were designed to facilitate efficient and rapid testing of various air injection configurations. These configurations aim to enhance thermal efficiency and significantly reduce emissions. The BSS system exhibits a thermal efficiency of 34 %, whereas the BUS system indicates a lower thermal efficiency of 29 % (Rapp et al., 2016). In comparison to cooking on a traditional stove, cooking with these types of stoves requires significantly less wood due to their higher thermal efficiency.

3.3. ACE–1 advance biomass cookstove

This stove is made of stainless steel and a forced air cookstove manufactured by African Clean Energy (ACE). This advanced cookstove has the capacity to burn a wide variety of different types of biomasses. One of the main features of this stove is that it gives its users the electricity and heat they need without giving off much smoke, which is good for their health. The ACE-1 cookstove offers the ability to access electricity, enabling them to charge their mobile phones and use the light from the LED accessory. The ACE-1 offers savings on electricity bills, making it a financially viable choice. The ACE-1 stove is capable of efficiently burning various types of dry solid biomass fuels, such as animal manure, agricultural residue, and wood sticks. This versatile feature of the stove helps reduce the reliance on wood fuel, which is often obtained through environmentally harmful practices involving deforestation (African Clean Energy ACE, 2022, 2022). The gasification process is made possible by a fan-driven technology that is built into the stove. The range has this technology built in. The fan pushes oxygen into the chamber through holes at the combustion chamber upper and lower ends. This makes the fire reach a temperature of about 1000 degrees Celsius, which is caused by the fan. The biomass starts to turn into gas and rise to the top, where it meets more oxygen and finishes the process of combustion (African Clean Energy ACE, 2022, 2022; Baltruschat, 2019). The cookstoves are expected to last between 8 and 12 years, depending on the extent of their usage (African Clean Energy ACE, 2022, 2022). The thermal efficiency of this stove is about 41.5 % (Engineering for change,).

3.4. Oorja advance cookstove

This stove was first made by BP (British Petroleum). Then, in India, First Energy Private Limited made some enhancements to it, and that company is the one spreading the word about it now (Mukunda et al., 2010). The outside of this stove's chamber is made of metal, and the inside is made of ceramic. The outside of this stove's chamber is made of metal, and the inside is made of ceramic. The heat shield is made of stainless steel. Agricultural waste is used as a fuel source in Oorja Cookstoves. The forced draught is made by a small electric fan with a battery that can be recharged. A speed controller for a fan is usually made with a switch that can be set to either the low or high position. The range came with both an instruction manual and an extra power source that could be charged. It is thought that more than 0.4 million stoves have been given out all over India. Overall, the performance of this cookstove is satisfactory with thermal efficiency of about 37.26 % (Clean Cooking Alliance,).

3.5. Philips HD4012 advance cookstove

A researcher named Paul van der Sluis working at the Philips Research Laboratories in Eindhoven came up with the idea for the Philips HD4012, which is a forced and top loading cookstove. The internal structure of the cookstove is built using ceramic materials, and the exterior is made of stainless steel. Biomass can be burned in the Philips stove with only minimal preparation, but in order to efficiently use fuel, it is necessary to break it down into smaller pieces measuring approximately 2.5 cm in diameter and 5 cm in length (Mukhopadhyay et al., 2012). A knob is located on the front of the stove and can be used to adjust the speed of the fan. The HD4012 requires access to an electrical outlet in order to be charged intermittently. The Philips stove was originally chosen because it performed well in laboratory tests conducted by the United States Environmental Protection Agency (EPA), where it was shown to be one of the least polluting stoves when compared to others utilizing industry-standard simulated cooking procedures. This result led to the initial selection of the Philips stove (Jetter et al., 2012). The Philips Stove has a thermal efficiency of approximately 39.4 % while the life spam of the stove is 5 years (Engineering for change,).

3.6. Mimi Moto cookstove

The Mimi Moto stove was made by a company in the Netherlands. It is a gasifier stove with forced draft that operates on biomass pellets as fuel. In 25 different nations across Asia and Africa, it has been used as a method of cooking that reduces pollution. It is one of only two biomass cookstoves that meet the parameters for efficiency, and total emissions that were established by the Water Boiling Test (WBT) in 2012 (C.S.U.A. B.C.L. Colorado State University, 2015). The design of the Mimi Moto incorporates two removable burning chambers to provide versatile cooking options. The larger chamber is intended for high-powered flame, while the smaller biomass chamber is designed for low power simmering. This thoughtful design allows users to adjust their cooking methods based on their specific needs, making the Mimi Moto a flexible and user-friendly cooking solution. In addition to its versatile cooking options, the Mimi Moto stove also features a built-in fan, which is powered by an external rechargeable battery pack. This fan aids in the gasification process, ensuring a clean and efficient burn. To support off-grid applications, the stove comes with a solar panel to charge the battery pack. This ensures that the stove can be used in remote locations without the need for traditional power sources, adding to its versatility and practicality. The gases that are taken out burn perfectly and cleanly because the biomass fuel is turned into gas instead of being burned directly. The stove is made from high-quality stainless steel and has long-lasting parts to make sure it will serve its purpose for many years. This method works extremely well. It has several burners, and each one can be taken out by itself. Because of this, you can get the most out of the fuel by using either the small burner for low-power simmering or the large burner for high-power cooking. This stove has an overall thermal efficiency of about 46.8 % (Mimi Moto – Clean cooking for al, 2022).

3.7. SSM F-18 force draft pellet cookstove

This cookstove model was introduced in 2018. The stove underwent testing in accordance with the ISO/IWA protocols using the Laboratory Emissions Monitoring System developed by the Aprovecho research center. This testing aimed to assess the stove's fuel consumption, cooking efficiency, and emissions. Chinese stoves are frequently only operated at high power and the SSM stove was designed for high power use. A flat bottom pot was used in all tests. The pot dimensions were 26 cm in diameter and 16 cm in height. The pot was filled with 5 L of water. A 6 mm channel gap sheet metal skirt was used with the pot. The pot skirt had a height of 15 cm. The stove was fueled with biomass pellets manufactured by Golden Fire. The pellets had a moisture content of 3 % (wet basis). The SSM stove does not have a chimney. It could be access to many different types of pellet material. Such as wood, rice husks, animals' dung, and straws. So maximumly provides the opportunity of using agricultural waste. Lifespan is up to 5 years.

Among all the advanced cookstoves, the common parameter among all is that the type of fuel used is common and they are force-draft operated. These advanced cookstoves make use of heat more efficiently and reduce CO and PM pollutants. Except for "Oorga" and "Philips" stoves, which have ceramic inner walls in the combustion chamber, they are made of steel. Wood fuel and agricultural residue are common types of fuel used in all advanced stoves. The thermal efficiency of each of these advanced stoves is based on various factors, making it hard to compare them. Based on their respective tier ratings, biomass cookstoves can be straightforwardly divided into three categories: traditional, improved, and advanced. Table 2 present the default values for different tier biomass cookstoves. Most traditional stoves are classified as either Tier 0 or Tier 1 models. The improved biomass cookstoves and the advanced biomass cookstoves will each have a tier rating of between 2 and 3, with tier ratings of between 3 and 5 respectively. The stove becomes more efficient, produces less carbon monoxide and particulate matter, becomes safer to use, and lasts less long as its tier rating rises, which indicates that it can be used for a longer period (B. Sutar, 2022). Table 3 contains the thermal efficiency of the commercialized biomass cookstoves available in the cookstove markets.

4. Technical parameters in biomass cookstove

4.1. Primary and secondary air inlets

In order to optimize the performance and efficiency of the biomass cookstove, careful consideration must be given to the design and positioning of the primary and secondary air inlets (Gutiérrez et al., 2022). These air inlets are necessary to provide air for combustion of biomass in cookstove. As the biomass cookstove mainly works on combustion process hence adequate amount of air required for that process and hence supply of air through primary and secondary air inlets is a critical area when designing biomass cookstoves. The primary air introduced in combustion zone of cookstove which determines the air-fuel ratio and help in pyrolysis process to form volatiles, while secondary air introduced to the combustion chamber to aid in the complete combustion of these volatiles (Muñoz et al., 2023; Gumino et al., 2020). Therefore, the design and placement of these air inlets play a crucial role in achieving optimal combustion efficiency and minimizing pollutant emissions. By carefully designing and positioning the primary and secondary air inlets, it is possible to achieve efficient combustion and minimize pollutant emissions in biomass cookstoves.

Table 2
Biomass cookstoves default values of voluntary performance (B. Sutar, 2022).

Tier	Thermal Efficiency	Safety Rating	Durability Rating	Pollutants	
				CO	PM
	%			(g/MJ)	(mg/MJ)
0	< 10	< 60	> 35	> 18.3	> 1031
1	≥ 10	≥ 60	< 35	≤ 18.3	≤ 1031
2	≥ 20	≥ 68	< 25	≤ 11.5	≤ 481
3	≥ 30	≥ 77	< 20	≤ 7.2	≤ 218
4	≥ 40	≥ 86	< 15	≤ 4.4	≤ 62
5	≥ 50	≥ 95	< 10	≤ 3.0	≤ 50

4.2. Air velocity

Air velocity plays a crucial role in the combustion process of biomass cookstoves, affecting both primary and secondary air velocities. The ratio of air to biomass and the velocity of the conversion between solids and gas can be influenced by the primary air velocity (Muñoz et al., 2023). Understanding the importance of secondary air velocity is crucial for ensuring the complete combustion of volatile substances produced during feedstock devolatilization (Hayyat et al., 2024).Based on the research results, it can be concluded that the emission of particulate matter is significantly influenced by the flow rate and velocity of secondary air injection. Increased velocity can enhance combustion efficiency and promote more complete combustion. However, it's important to note that increasing the overall velocity of secondary air may lead to local flame extinction, resulting in increased particle emissions (Hayyat et al., 2024; Zhang et al., 2018). In order to enhance the efficiency of combustion processes and minimize the release of particulate matter in biomass cookstoves, it is crucial to achieve the optimal velocities of both the primary and secondary air. Several studies have explored the correlation between variations in air velocities and their effects on combustion. These effects, in turn, have implications for the thermal efficiency and emissions rates within the system. It's worth noting that the optimal air velocity for biomass cookstoves can differ based on the specific designs employed. Regulating fan system and vent control are necessary for forced draft cookstoves to regulate primary and secondary air. On the other hand, it is challenging to control air velocities in natural draft cookstoves (Kumar et al., 2013; Lewis and Pattanayak, 2012; Deng et al., 2023).

4.3. Inlet area ratio

The performance of biomass cookstoves is greatly influenced by the Inlet area ratio (IAR). A significant amount of research has been conducted on IAR, utilizing experiments and numerical simulations to identify the optimal value. Various IAR values are being tested in experimental research to analyze their effects on performance indicators. Computational modelling utilizes conceptual and mathematical techniques to analyze the airflow and combustion within a cookstove. The goal is to simulate the effects of different IAR values using numerical methods. Based on this research, it has been discovered that the optimal IAR values differ depending on the type of biomass fuel, the extent of cookstove modification, and the intended cooking purpose of the stove. Multiple studies have confirmed that certain types of biomass fuel can achieve greater firepower and flameter, while also reducing CO emissions, by increasing the IAR. However, the optimal IAR value may vary for different scenarios. The critical value of IAR is found to be 0.70. Up to this value, both the firepower and flame temperature increase (Pande et al., 2020, 2022). However, for an IAR less than 0.7, the firepower decreases, the flame temperature saturates, and the CO emissions continue to rise.

4.4. Flame temperature

The flame temperature is an important factor that affects the

Table 3
Thermal efficiencies, fuel type and biomass material used in the commercialized cookstoves.

Advance cookstove name	Thermal efficiency	Emissions		Fuel type used	Material	Image	Image Reference
		PM (g/MJ)	CO (g/MJ)				
IITD	41.34 %	0.038	0.98	Wood Agri-Waste	Mild Steel	N/A	N/A
Berkeley Air Injection	29 – 34 %	0.61	8.21	Wood Waste	Stainless Steel		(Rapp et al., 2016)
ACE−1	41.5 %	101.1	0.82	Animal Waste, Corp Residue	Stainless Steel		(Engineering for change,)
Mini Moto	46.8 %	0.014	0.154	Wood and Agriculture Waste	Stainless Steel		(Mimi Moto – Clean cooking for al, 2022)
Phillips Stove	39.4 %	147.3	2.71	Corp Residue, Animal Waste	Ceramic and Stainless Steel		(Engineering for change,)
Oorja Stoves	37.26 %	0.128	1.12	Agriculture Residue	Ceramic and Metal		(Clean Cooking Alliance,)
SSM	51.1 %	0.022	0.69	Wood Agri-Waste	Stainless Steel		N/A

performance of biomass cookstoves. The flame temperature is directly related to the thermal efficiency of the biomass cookstove (Suhartono et al., 2018; Barpatragohain et al., 2021). Higher flame temperatures lead to more complete combustion, reducing harmful air pollution and increasing combustion efficiency. Flame temperature is reported to be increased when the biomass-air ratio tends towards the stoichiometric ratio (Muñoz et al., 2023). Also, the availability of oxygen in the biomass cookstove is a key factor that can affect the flame temperature; an increase in the excess air ratio can decrease the flame temperature (Memon et al., 2020). In addition, the type of biomass fuel used can also influence the flame temperature in a biomass cookstove. More importantly, the design of the biomass cookstove, including the previous described parameters such as air inlet ratio and their size, also affects the flame temperature, which can lead to variations in cooking performance and efficiency (Pande et al., 2020; Barpatragohain et al., 2021; Usman et al., 2023).

5. Application of design techniques in biomass cookstove

The development of modern design techniques in biomass cookstoves involves the application of scientific principles and methods to enhance their functionality and efficiency. Various methods, such as Design of Experimentation, Robust Parameter Design, and other advanced stove optimization techniques, have been developed to enhance stove performance and reduce emissions, making them more efficient and widely accepted. Utilizing these modern product design techniques can greatly improve the efficiency of biomass cookstoves by addressing the main factors that hinder their performance.

5.1. Design of experimentation

This is a systematic approach to establishing the cause-and-effect relationship between variables in the analysis of a process and its outcome. Recently, researchers have used the DOE to comprehend the impact of various factors on stove performance, including fuel type and amount, secondary air opening, and cross ventilation (Nayak and Roul, 2022). This information can then be used to optimize the design for maximum efficiency and minimum emissions (Ndécky et al., 2018).

5.2. Robust parameters design

RPD is a theoretical approach in design of experiments that helps establish the interaction of control factors to minimize the impact of uncontrollable factors. This process, known as RPD, has been utilized to enhance the performance of biomass cookstoves, ensuring optimal functionality. Bordoloi et al (Bordoloi et al., 2022). developed a comprehensive multi-response parameter to optimize a hybrid draft biomass cookstove. They stated significant improvements in terms of efficiency, with an overall increase of up to thirty percent. They also noted a reduction in emissions of Carbon Monoxide and Particulate Matter 2.5.

5.3. Advance optimization techniques

These techniques involve the use of end-to-end modeling and optimization efforts for the biomass cookstove design. The thermodynamic and heat transfer processes underlying stove performance are tightly coupled, which makes modeling a challenge (Sagouong and Tchuen, 2021; Yang et al., 2023). However, several numerical techniques have been introduced to optimize the performance of biomass cookstoves using commercial and open-source software (Ndécky et al., 2018; Datta et al., 2021).

6. Recent developments in biomass cookstove technology

In recent decades, cookstove design, modelling, and improvement have all taken place in various countries around the world thanks to scientific and technological developments made possible by research and development in all branches of science and technology. Several researchers have studied a few methodologies in the most recent years, including design methodology and materials.

Mensah et al (Boafo-Mensah et al., 2020). examined the performance of biomass burners with different combustion chamber materials. Fig. 2 shows designed model and material used for combustion chamber. Cylindrical cookstoves were made from common materials traditionally used for stove construction. The different thermal conductivities of these materials indicated that their capacity to transfer heat varied. Mild steel, aluminum, and ceramic were used to develop the combustion chamber with cylindrical holes. The water boiling test consisted of three distinct stages, namely high power cold start, high power hot start, and low power simmering, in order to assess the impact of different materials on the cookstove's efficiency. Ceramic has been identified as the optimal material for the combustion chamber of biomass cookstoves, exhibiting the maximum thermal efficiency and the lowest fuel usage among the three materials that were investigated. As far as the emissions are concerned, it has been recorded that CO and $PM_{2.5}$ are lower as compared to aluminum and mild steel.

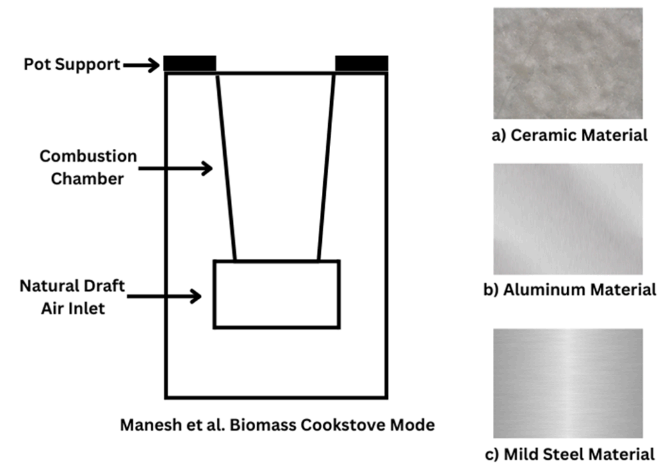

Fig. 2. Combustion chamber and relevant materials used by Mensah et al (Boafo-Mensah et al., 2020).

Beladiya (Beladiya, 2022) conducted a study where a swirl vane component, composed of galvanized steel, was integrated onto the upper part of the biomass stove when the stove was configured to run in natural draught mode as shown in Fig. 3. The six equally spaced swirl vanes with a 40-degree angle assist in deflecting the flow direction of gas, resulting in increased heat production and decreased smoke. The presence of a swirl has been found to facilitate the thorough mixing of secondary air and hot gases, leading to a more even distribution of heat beneath the pot and enhanced burning of the fuel. With the aid of a swirling flame, the upgraded biomass cookstove's efficiency is increased by 4 %, and the utilization of fuel, PM, CO, hydrocarbons, etc. is reduced. The addition of a swirl vane into a biomass cookstove exhibits the capacity to mitigate indoor air pollution and reduce fuel consumption, hence enhancing the health of those with limited financial resources.

Gupta et al (Gupta et al., 2020). developed a multi fuel biomass cookstove that feature two reactors integrated in a single assembly configured to run in natural draft. The schematic of multi fuel biomass cookstove is shown in Fig. 4. This gives users the option of adding fuel to the cookstove from either the top or the side-bottom of the appliance. The stove could burn multiple types of fuel at the same time. The efficiency of the stove was assessed by conducting experiments using various fuel sources such as dung cake, crop residue, wood, coal, and charcoal. While evaluating the various fuels previously discussed, the stove's thermal efficiency was found to be approximately 27.31 %, 24.58 %, 29.45 %, 34.72 %, and 32.59 % in consecutive examinations.

Kumar and Panwar (Kumar and Panwar, 2019) designed an efficient biomass stove that operates in a dual draught mode and was created by the two as shown in Fig. 5. The issue of an intermittent power supply to charge the battery of the blower has been remedied by designing the stove in such a way that it can operate in natural draught mode. This allows the battery to be charged without the blower having to be turned on. The issue could therefore be solved because of this. In the event that the battery has been charged to its maximum capacity, the apparatus is able to operate in the mode of forced draught. Users can use the cookstove because it can use more than one fuel, has a thermal efficiency of about 36.56–36.79 % when operating in forced draught mode, and has an efficiency of about 33.44 % when operating in natural draught mode.

Barbour et al (Barbour et al., 2021). present study involved the development and evaluation of a biomass cookstove, focusing on three different air injection configurations: over fire air injection, under fire air injection, and staged air injection (hybrid air injection) as shown in Fig. 6. Experimental and Computational Fluid Dynamics (CFD) analysis were used to look at how different air injection configurations affected

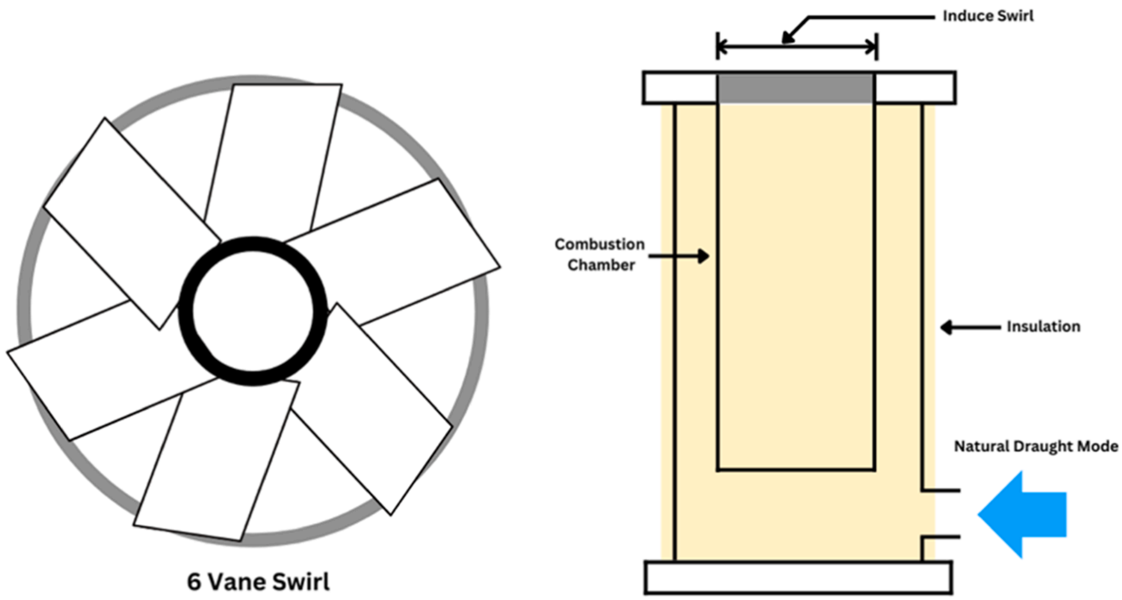

Fig. 3. Schematic of swirl vane instrument used in biomass cookstoves (Beladiya, 2022).

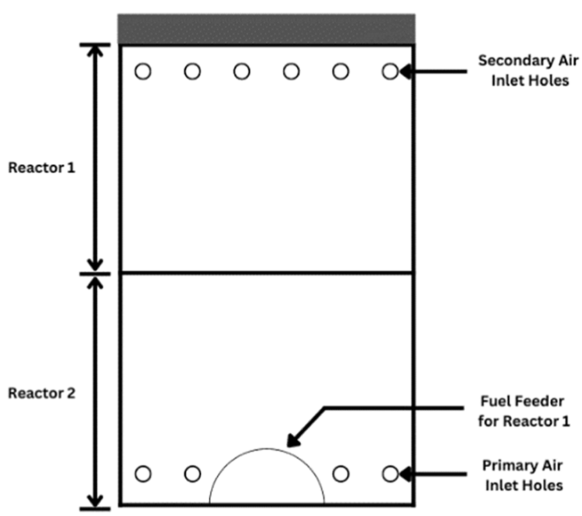

Fig. 4. Schematic of multi fuel biomass cookstove (Gupta et al., 2020).

the performance of biomass cookstove. Results show that forced air injection techniques can improve the efficiency of biomass stove by reducing emissions and complete combustion of biomass. Upon comparing the three air-injection strategies, it was seen that over-fire air injection exhibited the highest efficacy in reducing emissions. On the other hand, under-fire air injection showed the greatest enhancement in firepower and reduction in boiling times. Staged air injection, on the other hand, exhibited improvements in both emissions and burn rate. Moreover, it has been determined that the initiation stage of combustion is most crucial in the context of under-fire injection, as it is responsible for generating the highest level of emissions in forced-draft stoves. This is still an area that could use improvement. Table 4 contains the worldwide authors contribution in the advancements of biomass cookstoves.

7. Challenges and limitations in biomass cookstove technologies

7.1. Design limitations

One of the major challenges in biomass cookstove design is the lack of clarity in the design space. This highlights the limitations of standardized combustion chamber designs, varied algorithms, limited options for airflow control, and unclear usage cycles (Lombardi et al., 2017). The lack of standardized biomass cookstove design and altered calculations contributes to this problem, making it difficult to achieve consistent and efficient heat transfer during the cooking process. Without well-defined boundaries, it becomes difficult to enhance the efficiency and implementation of biomass cookstoves. Developing a well-structured layout can contribute to the creation of cookstoves that are environmentally friendly, pose no harm to the ecosystem, and are user-friendly (Rabby et al., 2023). In addition, limited options for airflow control contribute to the challenges of achieving a consistent and optimal cooking temperature. Flame distribution has been a major concern in biomass cookstoves, resulting in uneven temperature distribution and causing difficulties in cooking (Hayyat et al., 2024).

One of the challenges in biomass cookstove design is the lack of design capabilities for ash collection. This issue can lead to health problems for consumers due to small ash particles. With the absence of effective ash collection components, consumers may be exposed to harmful particulate matter while cooking, leading to respiratory issues and potential health risks. Another challenge in biomass cookstove configuration is the lack of information regarding fuel selection and properties. This information is crucial for understanding chemical properties, combustion, and heat transfer (Zhang et al., 2018). The lack of this data makes it challenging to improve the efficiency and performance of biomass cookstoves. A fundamental aspect that needs to be addressed in the advancement of biomass cookstove technology is the limited understanding of particulate matters. Specifically, there is a lack of information or research on emission reductions to guide emission modeling (Marchese et al., 2018). The lack of information in this area hinders the progress of cleaner-burning biomass cookstoves.

7.2. Computational modeling challenges

Computational or numerical analysis is currently the major breakthrough to get insights into biomass cookstoves before major production

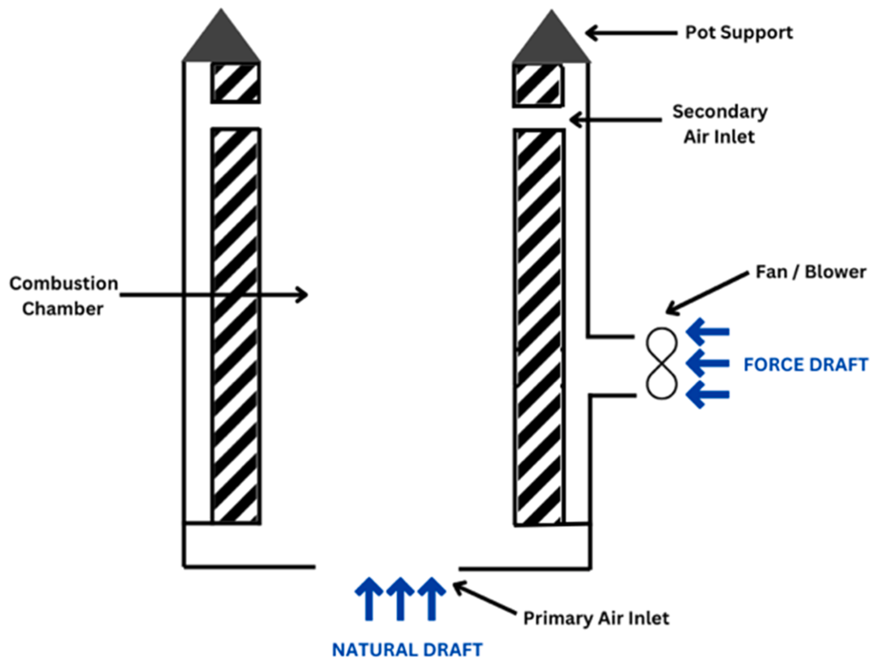

Fig. 5. Schematic of dual draught mode for biomass cookstoves (Kumar and Panwar, 2019).

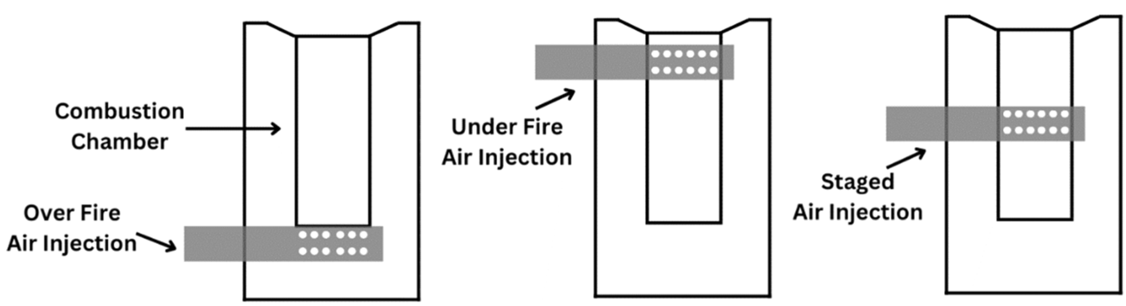

Fig. 6. Schematic of three air injection configuration (Barbour et al., 2021).

(Mekonnen, 2021). Although there has been much research on biomass cookstoves using numerical simulation using commercial software, there is a challenge associated with them. These numerical studies cost computational costs, and due to complex heat transfer combustions in biomass cookstoves, many studies are solely relying on homogeneous combustion of cookstoves. Also, due to the variety of fuels used in biomass cookstoves, the results of the results of these studies contradict the on-field performance of biomass cookstoves (Hayyat et al., 2024; Rabby et al., 2023). Most of these numerical studies in the field of biomass cookstoves are unable to fully capture the insights of the combustion process, heat transfer, and pollutant emissions in real-world biomass cookstoves due to complex computational methodologies and a lack of accurate data for model validation. The formation of ashes or soot in biomass cookstoves is another challenge that researchers and designers face in optimizing the performance of biomass cookstoves (Torres-Rojas et al., 2019; Benka-Coker et al., 2020). These kinds of impurities are hard to model and hence require more computational time and resources to get insights into the real-life performance of biomass cookstoves.

7.3. Repairing of cookstove

Advanced cookstoves have become among the most environmentally friendly biomass-burning cooking technologies now available on the market. They are also very efficient overall. Most gasifier stoves need electricity to work, which is different from traditional stoves and fireplaces. The cookstoves with solar powered integration hasn't held up as well as it should. A key question is whether the rate of installations is higher than what can be fixed. Another question is whether the company that makes the stoves will change the way they look and stop making replacement parts for older stoves. Dickinson et al (Dickinson et al., 2019). conducted a study in northern Ghana, it was observed that the batteries of Philips stoves began to exhibit signs of failure after a duration of one year. After a period of two years, a significant proportion of the batteries, specifically 62 %, had ceased to function. The manufacturer of the stove implemented alterations to its visual design and transitioned to a distinct battery model, resulting in challenges and increased costs associated with the procurement of previous battery iterations. Additional issues arose in the study, namely, a malfunctioning fan was observed in around 14 % of the stoves after a two-year period, while the solar charger exhibited non-functionality.

Mortimer et al (Mortimer et al., 2017). conducted a randomized controlled trial in a rural region of Malawi over a period of two years. The study involved two groups of equal proportions, aiming to examine the impact of Philips HD4012 stoves against the method of cooking over an open fire on the risk of pneumonia among children under the age of five. Similar difficulties were discovered. The targeted households were provided with two Philips stoves, a solar power system for the purpose of charging the battery that powers the stove fan, and comprehensive training on the proper utilization of the stoves, the research program

Table 4
Authors contribution in the advancement in biomass cookstove.

Name of researchers	Description of the advancement in biomass cookstove	References
Mensah et al.	The performance of biomass cookstove was examined with different combustion chamber materials. Ceramic has been identified as the optimal material for the combustion chamber in biomass cookstoves. The levels of carbon monoxide (CO) and fine particulate matter (PM2.5) are comparatively lower in relation to those of aluminum and mild steel.	(Boafo-Mensah et al., 2020)
Barbour et al.	The performance of three biomass cookstoves with over-fire, under-fire, and hybrid air injection configurations was examined computationally and experimentally. It was found that over-fire air injection reduced emissions the most, under-fire air injection increased firepower and decreased boiling times the most, and staged air injection improved both emissions and burn-rate.	(Barbour et al., 2021)
Gupta et al.	The Biomass cookstove has two reactors that are built into one unit. The stove could use more than one kind of fuel at the same time.	(Gupta et al., 2020)
Beladiya	The performance of biomass cookstoves was tested by incorporating a swirl vane instrument made up of galvanize steel on the top of the stove. It has been discovered that the swirl assists in mixing secondary air with hot gases, resulting in a uniform distribution of heat below the pot and cleaner fuel combustion increasing the efficiency upto 4 %	(Beladiya, 2022)
Kumar and Panwar	A dual-draft biomass stove shows more efficiency and is found to be user-friendly. This means that the battery of the fan can be charged without having to turn on the stove. The cookstove can be used because it can use more than one fuel and is about 36.56–36.79 % thermally efficient.	(Kumar and Panwar, 2019)

provided complimentary replacements and repairs promptly upon request. Throughout the course of the experiment, it was observed that each household receiving assistance required the service an average of four times. Over the course of the two-year trial duration, a total of 13, 192 cases of stove repair or replacement and 5259 instances of solar panel repair or replacement were recorded. The frequency of stove and its component breakdowns was unexpected to the researchers, given that the stove and its components were specifically designed for the users and their respective settings.

In most cases, the battery system of the cookstove is prone to failure. Over the following assessments conducted at 1/4, 1 and 2 years, a progressive decline in the proportion of families (73 %, 59 %, and 50 % in that order) reported that the Philips stoves satisfactorily fulfilled their cooking requirements The majority of surveyed homes, which voluntarily responded to an additional inquiry, reported utilizing the stove for a minimum of one meal every day on average over the course of the two-year follow-up period. The stoves' general condition of degradation was the main cause of the inability to use them for all cooking needs. Clark et al (Clark et al., 2017)., who researched semi-gasifier cooking stoves in China, give another example of how often stoves break down, even though stove users were asked a lot of questions and new stoves were designed repeatedly. The intervention package, which was given out in two steps, included a stove with a semi-gasifier that could be used to cook and heat water, as well as enough pellets to last for two years. According to Shan et al (Shan et al., 2017). the stove underwent a step-by-step design process involving five years in order to fulfill the ISO IWA's tier 3 voluntary performance standard for thermal efficiency as well as tier 4 voluntary performance standards for emissions and safety. The significance of the stove lies in its incorporation of an automatic igniting system and compact fan mechanisms, resulting in the production of a flame that closely resembles that of natural gas. The inclusion of a pellet hopper on the stove facilitated the cook's ability to conveniently introduce pellets during the cooking process. During the course of the program, it was necessary to carry out repairs on 27 % of the stoves from the initial stage and 48 % of the stoves from the next stage. The component that received the most frequent recommendations for repair was the automatic ignition system.

7.4. Real world performance variations

When stove emissions are tested in the lab, they are done in conditions that are both close to ideal and simplified. This usually results in lower emissions than when emissions are measured in the field. All the testing can be done with biomass in pellet form except for the first ignition phase; typically, there is no need for reloading, and the only observations that need to be taken are those taken during water boiling tests. One of the most interesting things is that the $PM_{2.5}$ emissions from advanced combustion stoves that burn wood fuels are very different in the lab and in the field. It has been reported that measurements of emissions conducted in real-world conditions exhibit a three to fivefold increase compared to emissions measured in controlled laboratory studies. Mortimer et al (Mortimer et al., 2017). found that fuel and load variability were identified as significant factors contributing to increased emissions. However, the variations in fuel and load little impact LPG burners and are entirely inconsequential for stoves powered by electricity. According to available data, it has been observed that in Uganda, the PM2.5 emissions originating from LPG stoves were found to follow with the emission target specified by the International Organization for Standardization's (ISO) International Workshop Agreement (IWA), specifically tier 5. However, it was noted that forced draft gasifier cookstove in the same region were unable to achieve the emission objective set for tier 2 (Johnson et al., 2019). According to Shen et al (Shen et al., 2018). it was discovered that a rural household in Cameroon possessed an aged LPG stove with a malfunctioning burner, however it still managed to comply with the tier 4 PM2.5 emission standard.

In the prior research conducted in rural Malawi (Wathore et al., 2017), measurements in the field were taken to assess emissions from various biomass stoves. The homes involved in the study were observed cooking under their usual conditions. The findings revealed that of the 4 kinds of domestic stoves examined, the Philips HD4012 stoves exhibited the lowest emissions. The remaining three stoves consisted of "traditional" stoves utilizing three-stone fires or basic mud stoves, as well as ACE 1, a forced draft stove that shares similar characteristics with the Philips stove. The Philips stove exhibited a reduction of 70 % in both PM2.5 and CO emissions compared to traditional stoves. The real-time scatter emission coefficient, that estimates the degree of light scattering resulting from particulate emissions, exhibited a pronounced increase at the onset of each cooking session. However, the peak performance of Philips and ACE 1 stoves outperformed performance of other stoves by at least ten times, and in some cases, it approached a differential of about 100 times during the first 20 % of the cooking process. As a result, the mean PM2.5 and CO emission factors, given in grams of each pollutant per kilogram of wood combusted, were reduced by 80 % and 65 %, respectively, when compared to the mean values observed for the Philips stove used in households. Similarly, wet wood emissions of PM2.5 and CO pollutants were found to be 76 % and 61 % lower, respectively, when compared to other conditions. The most efficient forced draft cookstoves had emission levels that were similar to what was seen in a controlled laboratory experimentation for basic improved biomass cookstoves. Several things hurt field performance when different kinds of fuels were burned under different kinds of conditions. The Philips stove failed to fulfill the International Standards Organization's IWA's tier 1 PM2.5 emission reduction goal, and only marginally complied with the tier 3 CO emission threshold.

In northern Ghana, the REACCTING project also let the cooks use local fuels on the Philips HD4012 stove to make local dishes. People say that matches and crop stalks were often used to light fuel. When dry wood was burned in a Philips stove in the field, it gave off two to four times as much $PM_{2.5}$ as it did in a lab. This was statistically the same as a three-stone fire, but the stoves gave off 46 percent less CO. The mean thermal efficiency of traditional three stone in real-world conditions were approximately twice as high as those observed in the laboratory, and comparable to the thermal efficiencies exhibited by Philips stoves. Emissions of elemental carbon, or CO, were more variable in Philips stoves. The researchers put this down to different user actions, like changing the fan speed, putting too much fuel in the stove, or not preparing the fuel well enough (Coffey et al., 2017). In a study done in China, the effect of reloading pelletized biomass on emissions was measured. The stove was equipped with an operating crank mechanism for the loading and reloading of pellets, as well as an electric coil heater located within the combustion chamber to initiate the ignition process (Deng et al., 2018). The laboratory based PM2.5 emissions shown a reduction of over 70 percent compared to the emissions observed in the field, while the emissions of CO demonstrated a reduction of 60 percent. During the experimental trials, the reloading of pellets was observed in both laboratory and outdoors conditions, resulting in an increase in emissions. However, it was noted that the disparity in emission levels was below 60 % for PM2.5 and 40 % for CO. In water boiling tests (WBT) in a lab, emissions went up as the number of pellets loaded went up. Field measurements showed that 30 percent of all $PM_{2.5}$ emissions came from reloading.

8. Points for further thought and discussion

Several studies have proposed and designed various stove components, including the grate, pot skirt, dampers, and others, with the aim of enhancing the combustion and heat transfer mechanisms of the stove through various approaches (Bryden et al., 2005; Roth, 2011; Lockman, 1998; Micuta, 1985; Baldwin, 1986). In recent years, there has been an increase in research focused on mitigating emissions, resulting in the emergence of an innovative stove technology referred to as "gasifier pyrolytic" stoves. The design of these stoves is based on the concept of micro-gasification. The process of gasification was used to produce and isolate the combustible gases derived from biomass. Subsequently, these gases were used as a gaseous fuel source to achieve the desired goals of improved efficiency and reduced emissions (Roth, 2011).

The recently produced advanced biomass cookstoves are often more expensive because they are the result of a higher level of technological development. These stoves include improved technological design elements, including as grates, insulation, forced airflow, and more robust materials, which collectively facilitate a more efficient combustion process and hence enhance the overall efficiency of these equipment. This category of appliances includes charcoal, wood, and pellet cookstoves. The implementation of cooking stoves that exhibit higher efficiency and lower costs holds significant promise in reducing emissions, improving public health, and mitigating the detrimental impacts on forests and deforestation rates. Hence, it is essential to undertake a comprehensive investigation into the heat distribution and thermal performance of a stove design inside a controlled laboratory setting. This study could help ensure that the provided cookstoves are better than the current ones. Therefore, it's important to create new stoves that are reliable, efficient, have low emissions, are durable, and affordable (Kumar et al., 2013).

It is recommended that smoke and other harmful emissions be cut down by making combustion more efficient. This can be done by making heat transfer more efficient, which will reduce the amount of fuel needed. It's possible that the new ideas of batch feeding and forced draught will make stoves more efficient overall (Bryden et al., 2005). When air comes into a stove through free convection, it is said to have natural draught. When air comes in through a fan, it is said to have forced draught. People cook on both kinds of stoves. The design of the stove enables optimal mixing of combustible gases. Consequently, those responsible for the stove's design must enhance its combustion efficiency through modifications to its structural design and the integration of novel materials. Conversely, the use of a stove equipped with a forced draft mechanism facilitates enhanced mixing of combustible gases and oxygen, promoting more efficient burning and ultimately lowering emissions (Kumar et al., 2013). In a study by Su et al (Su et al., 2023). explains the estimation of cavity volume in the gasification zone for coal gasification at various oxygen flow levels. A detailed techno-economic analysis (Wang and Zhang, 2023) and system optimization (Zhu et al., 2024b) is recommended for optimum energy efficiency, system design, and associated operating conditions of the stove.

8.1. Potential for advanced biomass cookstoves to eliminate CO and PM

Approximately 25 % of global black carbon (BC) emissions originate from the combustion of solid biomass for household activities like cooking and heating (Serrano-Medrano et al., 2018). Black carbon (BC) is a type of carbonaceous aerosol, which is primarily emitted due to the incomplete combustion of solid biomass, conventional fossil fuels, and other carbonaceous fuel sources (Ravindra, 2019), it's important to mention that the substance has a global warming potential 680 times greater than carbon dioxide (Pratiti et al., 2020). There exists scientific proof indicating that the mitigation of black carbon (BC) emissions may be the second most important driver of climate change, exceeded solely by carbon dioxide (Serrano-Medrano et al., 2018; Ravindra, 2019). Therefore, it is essential to make the switch to environmentally friendly cooking technologies to mitigate the emission of carbon dioxide and black carbon into the Earth's atmosphere. The use of technologically improved cooking stoves has the potential to play an important role in reducing the level of pollution resulting from biomass burning. This section will discuss the effectiveness of the Advance Cookstove in reducing emissions, specifically in terms of carbon dioxide equivalent. Kumar and Panwar (Kumar and Panwar, 2019) have developed an enhanced biomass cookstove including a dual mode. This innovation has demonstrated notable efficiency in reducing CO_2 emissions, with a range of 6.6–7.04 tons per year. Consequently, it represents a substantial advancement compared to existing stoves. The stove's innovative feature allows for effective use in both natural draft and forced draft modes, thereby optimizing stove performance. The use of the producer gas cookstove developed by Panwar and Rathore (Panwar and Rathore, 2008) for communal cooking results in a significant reduction of roughly 7.16 tons in annual carbon dioxide emissions. In comparison, the study conducted by Dissanayake et al (Dissanayake et al., 2018). revealed that a primitive enhanced cookstove, referred to as "Mirt," built with cement, showed the capacity to mitigate around 0.94 tons of carbon dioxide emissions annually. Over the course of a year, Ethiopia conserved 25 % of its total fuelwood use to achieve this reduction. The Ethiopian government has set a target of distributing 11.45 million stove units nationwide, with the aim of achieving a reduction in yearly carbon dioxide (CO2) emissions of around 10.77 million tons.

8.2. Adaptation of cookstove technologies as a potential substitute to LPG stoves

Developing an efficient and low emission cookstove is a debate for a long time for many researchers. Such cookstove with these kinds of abilities is known as advance cookstove as they use two-step process to turn biomass into gas that can be burned. In the initial phase, the combustion chamber facilitates the thermal conversion of biomass fuel, resulting in the production of a combustible gas. Afterwards, in the second phase, the gas is fully oxidized within the second-stage combustion chamber. Gasifier stoves are capable of producing combustible gas through a specific process (Roth, 2011). Even though the way they burn and the fuels they use are different, most gasifier stoves have strong flames that can be adjusted in the same way that liquefied petroleum gas (LPG) stoves can. Many people who use solid fuels see LPG stoves as something to aspire to because of how nice they look and how much of a status boost they give (Smith and Dutta, 2011). Before these stoves can be used to cut pollution, they must be widely used, other stoves that cause pollution must be used less, and low-polluting gasifier stoves must be widely used (Lewis and Pattanayak, 2012). On the other hand, they might be able to replace LPG with something cheaper and easier to get.

9. Potential research gaps

There are some important areas in the field of biomass cookstoves that require careful attention and examination. One of the notable shortcomings is the lack of consideration for the heat transfer mechanism in the design of biomass cookstoves. Ensuring the exhibition and complete burning of fuel in biomass cookstoves is crucial. Addressing this gap is crucial for the development of more efficient and effective biomass cookstoves that can have a positive impact on both the environment and the communities that rely on them. Although some studies have attempted to improve the efficiency of the cookstove by enhancing heat transfer, there are still several crucial areas that have not been thoroughly investigated. One aspect worth considering is the impact char combustion and molten ash particles on the post combustion process within biomass cookstoves. Despite the complex nature of the topic, further exploration is needed to fully understand the air supply for the ignition cycle in biomass cookstoves. It is important to focus on identifying the air supply zones within the cookstove to improve the combustion process and enhance efficiency. In addition, the significance of disruptions in flame is often overlooked when designing cookstoves. There is a need for further investigation in biomass cookstove designs in order to improve their performance during outside wind conditions. In order to address the existing gap in research, it is essential to utilize computational resources to investigate and enhance the performance of biomass cookstoves. By incorporating numerical techniques, a more comprehensive understanding of the burning system can be achieved, ultimately leading to the development of more efficient and environmentally friendly biomass cookstoves. By addressing these research gaps, we can contribute to the development of more sustainable and efficient cookstove designs.

10. Conclusions

In conclusion, it is clear that biomass cookstoves have the potential to solve the cooking energy crisis in many developing countries. The study provides a comprehensive overview of the different types of biomass cookstoves available globally, highlighting their specific advantages and disadvantages. It also explores recent advancements in this field, emphasizing that although biomass cookstoves are close to becoming a commercial product, further development is needed to make them a truly ideal cooking technology. The review emphasized the effectiveness of cutting-edge biomass cookstoves, which are more thermally efficient and produce fewer emissions, as viable alternatives to traditional cooking appliances. However, it also acknowledged several challenges associated with current biomass cookstove designs, such as issues related to design consideration, modeling of complex heat transfer analysis, and material-related issues. Overcoming these challenges will be crucial for improving the efficiency of biomass cookstoves and ensuring wider adoption in the future. This review highlights the importance of ongoing research and development in order to overcome present challenges and fully understand its potential sustainability as a solution to the increasing demand in emerging countries.

11. Future directions

- Leverage computational fluid dynamics (CFD) and modeling to make cookstoves faster, more accurate, and more efficient. Use these tools for sensitivity analysis to avoid design parameters that are too sensitive.
- Focus on making advanced biomass cookstoves cheaper and more cost-effective. Explore new designs and the use of easily accessible materials. Continue research on natural-draft cookstoves as potential low-cost options.
- Consider fuel availability in the design and production of cookstoves. Improve or create reliable small-scale pelletizers. Teach local communities how to repair and maintain these stoves.
- Develop standardized testing criteria and methods to evaluate and verify optimal values of various parameters, such as fuel type, fuel feeding rate, pot shape and size, and water quantity.
- Consider the unique characteristics of each community when designing the stove. Establish local standards and protocols alongside international ones to enhance the accuracy of cookstove evaluations.

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Xue Chunyu: Writing – review & editing, Validation, Supervision, Conceptualization. **Muhammad Ahsan Amjed:** Writing – review & editing, Software, Methodology, Investigation. **Fahid Riaz:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Investigation, Conceptualization. **Mohammad Alkhedher:** Writing – review & editing, Visualization, Validation. **Muhammad Farooq:** Writing – review & editing, Visualization, Validation, Investigation, Formal analysis. **Muhammad Sultan:** Writing – review & editing, Visualization, Conceptualization. **Guangqing Liu:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization. **Muhammad Usman Khan:** Writing – original draft, Validation, Supervision, Resources, Project administration, Conceptualization. **Umer Hayyat:** Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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Data availability

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Authors' contribution statement

All authors contributed equally to this research.

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