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Review on Biomass Cookstoves: Performance, Evolution, and Future Development

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Abstract

In developing countries, approximately 3 billion people rely on biomass for heating as well as cooking their food. Nearly 50% of the world's population relies on solid fuels for household heating and cooking by burning firewood in a traditional cookstove, which faces the problem of low thermal efficiency and high pollutant levels. Various efforts to increase thermal efficiency as well as to reduce the pollutant levels of a traditional cookstove have been performed. Many published papers on developing biomass cookstoves have been studied and cited in this review paper. According to those published papers, it can be figured out that there are three generations of the biomass cookstove, i.e., a traditional cookstove, an improved cookstove, and an advanced cookstove. Many designs have been proposed to obtain the best performance of the cookstove. This present review paper aims to discuss and summarize various works in developing a high-performance cookstove, including various designs and challenges of the current development. Hopefully, this review article will give more insight to those who are interested in maturing a clean and eco-friendly biomass cookstove.

Index-words: *Biomass, Cookstove, Development, Eco-friendly, Pollutant.*

I. Introduction

The rapid growth of the world population leads to a rising stable food supply [1], which causes a speedy increase in heat energy demand for cooking. It is believed that renewable energy is one of the options that can accelerate the transition to sustainable energy with reduced emissions, enhance energy access, increase energy security, and mitigate climate change [2], [3]. The escalating heat energy demand reinforced the reliance on biomass as a renewable energy resource and the primary source of energy for domestic cooking [4]. Biomass, one of the most promising and widespread renewable energy sources [5], [6], has been used for centuries, from traditional applications such as heating and cooking to modern utilization such as electricity and biofuel generation [7]. Nearly 50% of the world's population relies on solid fuels for household heating and cooking [8]. Agricultural waste and woody materials residues are frequently used as an energy source [9]. Besides being a clean and renewable energy source with the advantages of abundant raw materials, low pollution, and near-zero CO_2 emissions, biomass is also a significant contributor to the global energy transition [10]. Biomass gasification technology is one of three urgent pursuits of sustainable energy solutions in green hydrogen technologies, which has been comprehensively modeled using the Fuzzy VIXOR model by Tamtam & Tourabi [11]. Their finding provided theoretical insights into decision-making models and practical guidance for policymakers and stakeholders to advance green hydrogen technologies.

In developing countries, about 2.7 billion people rely on biomass, including wood, charcoal, tree leaves, crop residues, and animal dung, for cooking [12]. In Indonesia, nearly 43% of the population cooks food using firewood [13]. The situation is not likely to change in the future since the high price of LPG,

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which makes it unaffordable for poor people in developing countries [14], [15], [16], [17], [18]. Cooking with biomass is predicted to increase significantly in 2030 [19]. Mostly, people burn biomass fuel in a traditional cookstove for cooking due to its simple construction and ease of use [20], [21]. However, traditional biomass cookstoves have problems of low thermal efficiency and high pollution levels. Only 5-15% of the heat from fuel burning is used effectively for cooking in the traditional biomass cookstove. Furthermore, the traditional biomass cookstove emits particulate matter and CO at high levels [22], which may cause a negative impact on human health and on climate change [23], [24]. Products of incomplete combustion from these fuels have significant impacts on air quality, human health, and regional climate change [25], [26]. Chronic obstructive pulmonary disease in adults and an increased risk of pneumonia in infants and young children can be affected by exposure to carbonaceous particulate matter from the burning of biomass [27].

In order to address the problem of the traditional biomass cookstove, various works to increase thermal efficiency as well as to reduce particulate and CO emissions have been performed. Many published papers on developing biomass cookstoves have been studied and cited in this review paper. According to those published papers, it can be figured out that there are three phases of evolution of the biomass cookstoves, i.e., a traditional cookstove, an improved cookstove, and an advanced cookstove. A traditional cookstove was used since early ages when human cooked their meat on the open fire above a pyramid of arranged firewood. Starting in the 80s, improved cookstove programs have been reported to be active in 160 nations globally in 2011 [28]. Meanwhile, the most recent development in biomass cookstoves is the gasifier cookstove.

Many designs have been proposed to obtain the best performance of the cookstove. This present review paper aims to discuss and summarize various works in developing a high-performance cookstove, including various designs and challenges of the current development. Hopefully, this review article will give more insight to those who are interested in developing clean and eco-friendly biomass cookstoves.

II. *Performance evaluation*

Generally, the performance of biomass cookstoves in terms of thermal performance and emission performance is tested using the Water Boiling Test (WBT) method [29], [30], [31], [32], [33]. Thermal performance of the cookstove relates to fire power, fuel consumption rate, burning rate, and thermal efficiency. Meanwhile, emission performance is evaluated in terms of CO emission, particulate matter ($PM_{2.5}$) emission, and the CO/CO_2 ratio.

A. *Water Boiling Test*

Water Boiling Test (WBT) is conducted in three phases, i.e., cold start, hot start, and simmering, which immediately follow each other as shown in Figure 1. According to WBT version 4.2.3 [34], the entire WBT should be conducted at least three times for each stove, which constitutes a WBT test set. In the cold start-high power phase, a pre-weighted biomass fuel is burnt in a cookstove at room temperature to boil a measured amount of water in a pot. In a hot start, the pot is then replaced by a pot filled with a measured amount of water at room temperature while the cookstove is already hot. Meanwhile, the simmering phase provides the amount of fuel required to simmer a measured amount of water at just below the boiling point for 45 minutes. National Indonesian Standard (SNI) 7926-2013 [35] adopts the WBT version 4.2.3 protocol to conduct biomass cookstove performance test. Meanwhile, in the Chinese WBT protocol, there is only one test phase. Once fuel is ignited, the pot with 5 L of water and the lid is put onto the stove, and the test starts. When the water temperature reaches the boiling point, the pot cover is removed. But the remaining fuels are left in the stove chamber and burned. The test ends when the water temperature decreases to 5 °C below the boiling point [36].

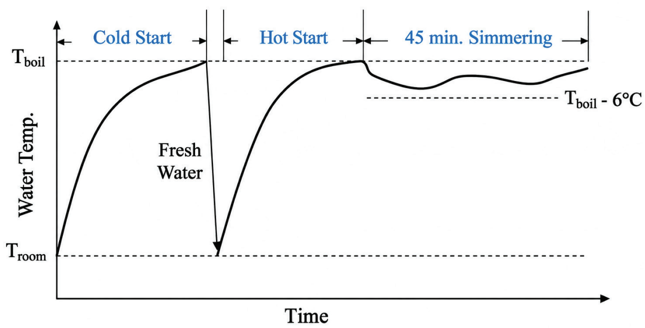

Figure 1: Temperature during the three phases of WBT.

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SNI National Indonesian Standard (SNI) 7926-2013 of WBT is similar to WBT version 4.2.3 and the African WBT protocol, which uses three-phase tests, and differs from the Chinese WBT, which uses only one phase test. Meanwhile, the Indian WBT standard uses a continuous batch/continuous burn protocol. Due to combustion and heat transfer mechanisms differing between the WBT 4.2.3 and Chinese WBT, evaluating the exact same cookstove under both protocols yields vastly different thermal efficiency and $PM_{2.5}$, CO emissions. Empirical data showed that cookstoves tested under the Chinese protocol consistently report statistically higher thermal efficiency than when tested under the WBT 4.2.3. The longer burning duration of the Chinese test allows the stove chamber to reach a steady, optimized internal temperature, minimizing transient energy loss. Cookstoves generally show lower pollutant emission factors ($PM_{2.5}$ and CO) under the Chinese protocol. Because the WBT 4.2.3 includes a low-power simmer phase, it forces the biomass into smoldering conditions (incomplete combustion due to restricted airflow), resulting in spiked emissions. The Chinese protocol keeps the stove operating at a continuous high-temperature fire, which cleanly combusts volatile gases and lowers emissions.

B. *Thermal performance*

- **Fire power:**
  Firepower (FP) is the equivalent dry fuel energy consumed by the stove per unit of time [37], [38] and expressed as

$$FP = \frac{m_f \times LHV_f}{\Delta t} \qquad \text{(kW)} \qquad (1)$$

- **Fuel burning rate:**
  Fuel burning rate is defined as how fast the fuel is completely burnt and expressed as

$$FBR = \frac{m_f}{\Delta t} \qquad \text{(kg/s)} \qquad (2)$$

- **Thermal efficiency:**
  Thermal efficiency is a ratio of useful energy for heating and boiling to the maximum possible heat released by the fuel, and is expressed as

$$\eta_t = \frac{(m_w \times c_{p,w} \times \Delta T) + (m_v \times h_{fg})}{m_f \times HHV_f} \times 100\% \qquad (3)$$

where m_f is the mass of dry fuel consumed (kg), LHV_f is the lower heating value of the fuel (kJ/kg), and Δt is the duration to boil 5 kg of water in a WBT pot (s), m_w is the mass of water in a pot (kg), $c_{p,w}$ is the specific heat of water (4.186 kJ/kg°C), ΔT is the increasing of water temperature (°C), m_v is the water vapor (kg), and h_{fg} is the latent heat of vaporization of a water (2260 kJ/kg) [37], [39].

C. *Emission performance*

Carbon monoxide (CO) and particulate matter ($PM_{2.5}$) emissions are measured in exhaust flue gas. The cookstove is tested under the hood connected to the exhaust pipe as shown in Figure 2. The tested cookstove is placed under the hood. Flue gas is sucked by the exhaust fan and passes through the CO and CO_2 sensors, and the $PM_{2.5}$.

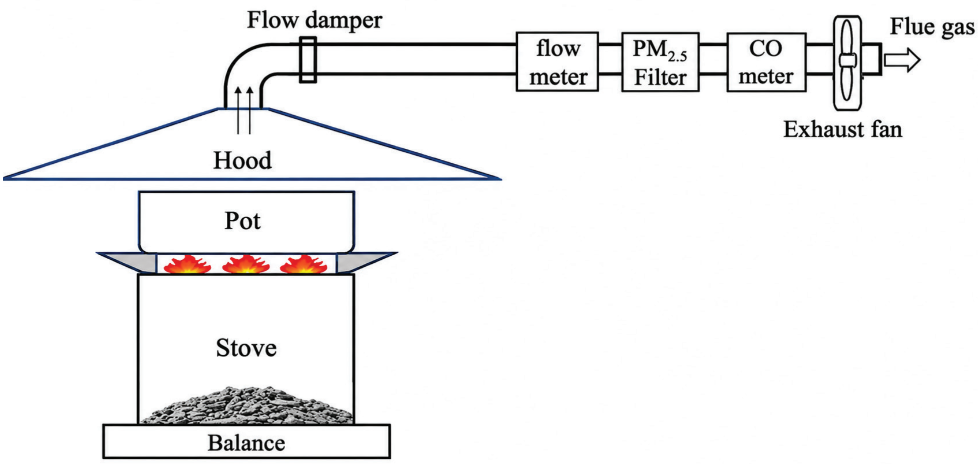

Figure 2: Measurement setup for CO and $PM_{2.5}$ emission.

- **CO emission:**
  The level of CO emission in flue gas is stated as the mass of CO (g) per unit mass of fuel consumed (kg)

$$CO = \frac{m_{CO}}{m_f} \quad \text{(g/kg of fuel consumed)} \qquad (4)$$

- **$PM_{2.5}$ emission:**
  The level of $PM_{2.5}$ emission in flue gas is stated as the mass of $PM_{2.5}$ (mg) per kilogram of fuel consumed (kg)

$$PM_{2.5} = \frac{m_{PM2.5}}{m_f} \text{ (mg/kg of fuel consumed)} \qquad (5)$$

where m_{CO} and $m_{PM2.5}$ represent mass of CO (g) and mass of $PM_{2.5}$ (mg), and mf represents mass of fuel consumed (kg).

D. Performance controlling design parameters

Instead of using clay as a stove's body, improved and advanced biomass cookstoves use metallic or ceramic materials. Furthermore, the natural air supply system in traditional stove design shifts to a forced and controlled air supply system design in improved and advanced stoves.

1. Material of the cookstove

Due to limited access to modern cookstoves for cooking, poor people in remote areas use a clay cookstove or a brick cookstove. Phusrimuang and Wongwuttanasatian [40] investigated the performance of the conventional stove made of brick with rectangular walls. The stove has a double-wall construction filled with rice husk ash as an insulator with a thermal efficiency of 15.17%. Kalyesubula [41] developed an invention of an Extra Energy Saving (EES) stove, which allows for fuel substitution and aligns with the recommendations of the Kyoto protocol. Jetter and Kariher [42] investigated the brick rocket stove developed by ARC. The stove has a combustion chamber made of insulative bricks that are light enough to float on water. The light-weight bricks were designed to minimize heat loss compared to heavier materials. They found that the 6-brick stove has lower emissions of all pollutants except $PM_{2.5}$ over the 3-stone fire during the low power phase of testing.

The efficiency of the cookstoves is largely influenced by the materials used for the construction of the cookstove [32]. Instead of using clay or brick, cookstove designers prefer metallic material for the cookstove body. Kole *et al.* [43] fabricated a metal cookstove from sheet metal with a thickness of 1.5 mm and tested it on coffee husk and rice husk feedstock. They reported the stove has an average thermal efficiency of 29% and 28% and emitted CO of 263 ppm and 235 ppm using coffee husk and rice husk, respectively. Yuntenwi *et al.* [44] mentioned that the type of stove exhibited a stronger effect on the total emissions than did the moisture level in the fuel. Pasha *et al.* [38] designed a coaxial cylinder Tchar cookstove, in which the inner and outer cylinders of the stove were fabricated from Stainless Steel plate. They obtained the thermal efficiency of the Tchar stove was 39.64±2.29% for the cold start high power phase and 51±3.12% for the low power simmering phase, respectively. Suresh *et al.* [45] reported that the thermal efficiency of a mild steel cookstove was in the range of 30-35% for different types of solid biomass fuel. Febriansyah *et al.* [46] reported the performance of the Gama cookstove, which was made from an iron plate. The stove had an efficiency of 66.63% using palm kernel biomass. Thermal conductivity and specific heat capacity of the cookstove material have to be considered in the material selection of the cookstove. The material used for the cookstove should have low thermal conductivity and high specific heat capacity to minimize heat loss from the combustion chamber to the surrounding through the body of the cookstove. Reducing heat loss could increase the temperature inside the cookstove and increase thermal efficiency. It was believed that energy-efficient biomass cookstoves were promoted as intermediate technologies that would alleviate the environmental, socio-economic, and health burdens of traditional cooking [47].

2. Primary air supply of the cookstove

Low thermal efficiency and high emission levels of a biomass cookstove are primarily affected by an uncontrolled air supply for combustion. The amount of air supply for biomass combustion plays an important role in determining thermal efficiency and emission levels of a cookstove. Thus, it is necessary to use a controlled amount of air in order to overcome the problems, such as using a chimney or controlled forced air combustion. A chimney provides draft for the suction of air into the cookstove and to remove flue gases from the kitchen. While the draft directly depends on chimney height, a larger diameter results in greater mass inflow of air due to a larger area and a reduced frictional pressure drop through the chimney. The height and diameter of the chimney must be so chosen as to balance the chimney draft with the air required for combustion and the frictional pressure drop, resulting in its best performance. A more effective method for controlling the amount of air for combustion is by using forced draft air.

Forced draft stoves are considered a viable option to overcome these problems [48]. Raman *et al.* [49] tested three forced draft stoves using fuel wood and coconut shell. They stated that a forced draft cookstove increases both heat transfer rate and combustion efficiencies simultaneously and recommended that forced draft stoves must be carefully designed and optimized for higher efficiencies. Deng *et al.* [50] compared a laboratory and field measurement of the effect of forced draft on $PM_{2.5}$ and CO emission of a Tsinghua University (THU)" cookstove. Field tests with varied fuel reloading modes yielded over 70% higher $PM_{2.5}$ emissions and 60% higher CO emissions, compared with no reloading laboratory tests. This discrepancy was caused by fuel reloading during the field test. Susastriawan *et al.* [51] tested the effect of a forced draft cookstove on the CO/CO_2 ratio using a briquette of coconut shell. The results show that better combustion occurs at a higher primary air flow rate and produces less CO and more CO_2. Thus, CO/CO_2 in flue gas reduces with increasing primary air flow rate. A lower CO/CO_2 ratio in flue gas indicates more complete combustion, hence better performance of the cookstove. A similar trend of reducing CO/CO_2 when increasing air flow rate during corn combustion was also obtained by Meng *et al.* [52]. By comparing the natural draft and the forced draft cookstove, Kirch *et a*l. [53] stated that high efficiency and low emissions of incomplete combustion can only be achieved with high controllability of the air flow in the different phases of combustion. Higher primary air was proven to have positive effects on particulate matter and carbonaceous fraction emission reduction [25]. According to Jain and Sheth [54], the formulated recipe air flow rate was able to improve the thermal efficiency and the operation time of the cookstove. Air flow rate can influence the oxidation rate of the gasification process, which impacts the gasifier temperature. Conversion of biomass is affected by process temperature. Balasubramanian & Sivakumar [55] found that temperature plays a crucial role in influencing biomass conversion into methane and carbon dioxide production during biomass anaerobic digestion. Laboratory studies of wood-burning cookstoves demonstrate that secondary air injection can greatly reduce the emission of harmful air pollution, but these experimental advancements are not easily translated into practical cookstove designs that can be widely adopted [56]. Regular user training may be necessary to maintain the higher level of the stove's performance [57].

III. Design evolution

A. Traditional cookstove

Since early ages, people have roasted and heated their meat on an open fire above the pyramid arranged firewood [58]. This open fire cooking lacked proper control over the fire exposure to heat and smoke, as well as fire hazards. The problem was encountered while developing a shielded fire, i.e., a traditional three-point fire cookstove. Traditional cookstoves are designed in rudimentary or primitive forms [59], in terms of a primitive cookstove. The construction of the traditional cookstove leads to a combustion process inside the cookstove being non-ideal, thus, favoring incomplete combustion [60]. The traditional versions of cookstoves are highly inefficient [12] and have low thermal efficiency [61], [62]. The thermal efficiency of the three-point cookstove was limited to 5-15% [63], or in other words, the three-point cookstove released about 5-15% heat from the total biomass consumed [64]. Due to the low efficiency of traditional biomass cookstoves, large amounts of firewood are used, resulting in high indoor air pollution, greenhouse gas emissions, and rampant deforestation [62]. Besides low thermal efficiency, incomplete combustion of biomass in the traditional cookstove releases carbon monoxide (CO), nitrous oxide (N_2O), methane (CH_4), polycyclic aromatic hydrocarbons (PAHs), particles composed of elemental carbon or black carbon, and other organic compounds [65], which often disproportionally affect women and children [66]. In developing countries, poor and rural families face extreme health and safety risks when cooking over traditional open fires or with primitive metal cookstoves [67].

B. *Improved cookstove*

The second generation of biomass cookstoves is an improved cookstove. Improved means biomass fuel saving and less emission, hence mostly improved cookstoves target low fuel consumption, high thermal efficiency, and low pollution [68]. Gizachew and Tolera [69] conducted a study to assess the determinants of households' decision for adoption of improved cookstoves (ICS) in the Bale Eco-Region of Ethiopia. They obtained CO_2 emission reduced 0.494 tons annually by using an ICS. Boy *et al.* [70] modified a conventional Plancha cookstove by attaching a baffle in the stove's combustion chamber, which resulted in 12% improvement in overall thermal efficiency. In five-day tests of routine cooking, the modified Plancha was found to use 39% less fuel wood than the open fire. Singh *et al.* [71] found that the mud improved cookstove was an appropriate intervention to reduce $PM_{2.5}$ and CO in rural kitchens in Nepal. Alam and Chowdhury [72] modified the traditional cookstove usually used by the people in the village of south-western Bangladesh. The improved cookstove is built with good clay subsoil, which has two chambers and a chimney. The use of improved cookstoves caused a reduction in wood fuel use per day and reduced the cooking time by 45 minutes per day. *Mamuye et al.* [73] investigated the emission and fuel use performance of two improved cookstoves, i.e., Merchaye and Lakech charcoal cookstoves. Both Merchaye and Lakech cookstoves reduced emissions of CO, CO_2, and $PM_{2.5}$ in comparison to a traditional charcoal cookstove. The specific fuel consumption (SFC) of Merchaye and Lakech was also reduced in comparison to a traditional charcoal cookstove. Wassie and Adaramola [74] examined the potential wood fuel savings and environmental effects of three ICSs (Mirt, Gonziye, and Tikikil) in rural Ethiopia. They reported that the use of those cookstoves could reduce households' wood fuel consumption on average by 1.72-2.08 tons per household per year. These fuelwood savings turned to potential emissions reductions of 2.82-3.43 tCO2e per cookstove per year.

Proper use and regular maintenance of the cookstove are essential in order to provide long-term benefits, ensuring efficiency and durability of the cookstove. It is important to follow the instructions for maintenance and troubleshooting in the manual book of the improved cookstove. For example, empty the ash and residue from the combustion chamber once the stove is completely cool, and wipe down surfaces to remove dirt, grease, and buildup of ash. Ash buildup and neglected servicing reduce efficiency and reliability, and inspect the cookstove routinely for signs of damage, wear, or rust, and replace faulty parts promptly [75].

The improved cookstoves can play a crucial role in improving rural households' welfare. As improved cookstoves decrease rural households' firewood needs, it is plausible that households will spend less time and monetary resources collecting firewood, and can reallocate these resources to other productive activities [76]. Laboratory studies have shown that improved cookstoves may offer reductions in fuel use, emissions of carbon monoxide (CO) and fine particulate matter ($PM_{2.5}$) [77],[78]. The use of an improved wood cookstove is likely to be a sustainable way to achieve an appropriate minimum level of energy access for cooking purposes for the poor people in rural areas [79]. Transitioning from traditional biomass cookstoves to improved biomass cookstoves revealed that they are highly economically viable, delivering massive societal and financial returns. Global evaluations consistently showed that the social and private benefits of improved cookstoves outweigh their procurement costs by ratios up to 11.4:1 [80]. The use of an improved cookstove allows significant savings for the family budget up to 50% of the total annual cooking energy expenditure [81]. However, these economic realities mean that technology selection for a given region or project must be grounded in site-specific techno-economic assessment rather than generic claims of cost-effectiveness [82].

Although an improved cookstove gives benefits in reducing greenhouse gas emissions and household cooking expenditure, several rural people face problems in adopting this technology. It was found that rural households face significant barriers in integrating clean cooking energy technologies, including financial constraints, infrastructural limitations, socio-cultural norms, technological challenges, and policy deficiencies. The obstacles to adopting clean cooking energy technologies in lower-middle-income countries arise from both intra-rural and inter-rural household barriers [83].

To move a household from a traditional three-stone cookstove to an improved biomass cookstove, programs must trigger a shift in habitual routines. Practitioners use targeted behavior change communication frameworks to address specific psychological barriers, such as training that must include public, community-wide cooking demonstrations where respected village leaders cook local staple foods using the improved cookstove.

The economic viability of improved biomass cookstove programs in developing nations depends fundamentally on carbon finance mechanisms. Carbon finance shifts the commercial paradigm by monetizing the environmental externality of avoided greenhouse gas emissions. In Indonesia, the relative price of the three-stone fire cookstove, the Keren/Rocket-type improved cookstove, and the Forced-draft Top-Lit Updraft (TLUD) gasifier cookstove are $2, $30, and $120, respectively.

C. *Advanced cookstove*

Recently, a more advanced biomass cookstove has been developed based on the gasification process, called the biomass gasifier cookstove. Unlike conventional cookstoves, where biomass is burnt directly to generate heat, biomass experiences a gasification process to generate syngas, followed by burning of the syngas to generate heat in the gasifier cookstove. Figure 3 shows a schematic diagram of the working principle difference between a traditional biomass cookstove and a gasifier cookstove. In a gasifier cookstove, biomass is thermo-chemically converted to syngas, which typically contains combustible gases CO, H_2, and CH_4. These combustible gases formed during the reduction process of gasification through the Bouduard reaction (R1), the Water-Gas reaction (R2), the Water-Gas Shift reaction (R3), and the Methanation reaction (R4) [84]. Boudouard and Water-Gas reactions are endothermic reactions, meaning they absorb heat to proceed. Meanwhile, Water-Gas Shift and Methanation reactions are exothermic reactions, meaning the reactions release heat during the reaction. The molar fraction of CO, H_2. CO_2 and CH_4 in the syngas are affected by biomass type, fuel moisture content, and operating parameters (such as air fuel ratio and gasification temperature). Syngas generated from biomass gasification is burnt in a burner to generate flame and heat. Since combustion of syngas is cleaner than direct combustion of biomass [85], it makes a gasifier biomass cookstove get increasing attention nowadays.

$$C + CO_2 \rightarrow 2CO + 172\ kJ/mol \quad (R1)$$

$$C + H_2O \rightarrow CO + H_2 + 131\ kJ/mol \quad (R2)$$

$$CO + H_2O \rightarrow CO_2 + H_2 - 41.2\ kJ/mol \quad (R3)$$

$$C + 2H_2 \rightarrow CH_4 - 74.8\ kJ/mol \quad (R4)$$

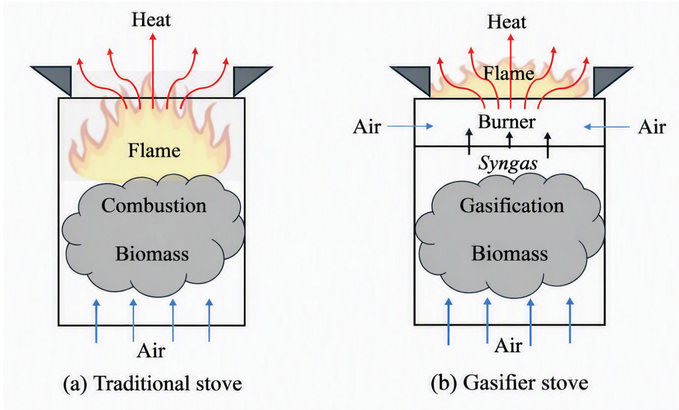

Figure 3: Traditional vs gasifier cookstove.

Several biomass gasifier cookstoves have been developed worldwide. A top-lit gasifier cookstove was developed and tested for its performance using feedstock of eucalyptus, sawdust, cow dung briquettes, and bamboo [86]. The stove thermal efficiencies were 32.30 %, 31.5%, and 26.25% for eucalyptus, sawdust-cow dung briquette, and bamboo, respectively. A batch inverted downdraft gasifier cookstove for rice husk was designed, fabricated, and evaluated by Osei *et al.* [87]. Performance in terms of thermal efficiency and CO/ CO_2 ratio was investigated using a water boiling test (WBT). They revealed thermal efficiency varying between 30.5-38.1%, and the average CO/CO_2 ratio was 0.055. Other, a reverse downdraft gasifier cookstove was developed, and its combustion process was evaluated by Kirk *et al.* [88]. They observed that more primary air and/or a deeper fuel bed reduces tars in the producer gas and increases the combustion efficiency, especially from low-ash-containing biomass. Meanwhile, the cookstove with optimized air hole configurations (14–18 holes, 10–20 mm diameter) and constructed using advanced materials, including fire clay bricks and fiber cement, has been fabricated, resulting in thermal efficiencies of up to 39 % [89]. The air distribution between the gasifier and the burner was important, and there was an optimum distribution ratio [90]. The top lit updraft gasifier cookstove using primary and secondary air has a thermal efficiency of up to 48.9% with a CO level of 2.7 g/ MJd and a $PM_{2.5}$ level of 194.8 mg/MJd [91]. Almost similar CO level of 2.75-2.78 g/MJd from the top

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lit updraft gasifier cookstove was also found [92]. Wang *et al.* [93] found an updraft gasifier cookstove with a thermal efficiency of 36.5% and a maximum power output of 1.8 kW. Ifeanyichukwu *et al.* [94] found that fan control and charcoal weight significantly affected efficiency and boiling time. Optimal settings were found to be a fan control of 3.1, charcoal weight of 0.65 kg, and use of natural lump charcoal, achieving an efficiency of 40.2% and boiling time of 11.6 minutes. Destaw *et al.* [95] reported that the thermal efficiency of improved biomass cookstoves had shown the highest value with an average of 31%, while the three-stone cookstove had a thermal efficiency of 13%. In biomass gasifier cookstoves, biomass moisture content plays an important role since it affects the syngas lower heating value (LHV). The higher the LHV, the better the cookstove performance. Thakkar & Singh [96] found that the biomass with the lowest moisture content of 8.3 wt.% had the highest syngas LHV of 4.6 MJ/m^3 at the ER of 0.4, while the biomass with the highest moisture content of 25.6 wt.% had the lowest syngas LHV of 3.1 MJ/m^3 at the ER of 0.2. Carbon conversion efficiency, cold efficiency, and gas yields were all considerably affected by the rise in biomass moisture content.

Other advanced cookstove development is an integrated cookstove-thermoelectric generator. Heat loss from the stove wall is utilized as a heat source for a thermoelectric generator (TEG) to generate electric energy. Mal *et al.* [97] developed and evaluated a 5 W thermoelectric generator (TEG) integrated forced draft biomass cookstove. The generated electricity was stored in a Li-ion battery and used further for running a 12V DC. fan, lighting an LED light, and charging a mobile phone. Fan power by TEG can be applied to supply forced air combustion to the stove [98], [99]. Li *et al.* [100] developed a prototype of a cookstove-powered thermoelectric generator (STEG). The measured maximum electricity power was 12.9 W, and the thermoelectric efficiency lies between 2.4% and 2.8% when the temperature difference ranges from 119 °C to 147 °C. The 4 W generator cookstove was developed and able to charge mobile phones, lights, and radios [101], [102], [103]. Najjar and Kseibi [104] found the maximum power output to be about 7.88 W and an average overall efficiency of about 60 % of cookstove using wood, manure, or peat. Lertsatitthanakorn *et al.* [105] studied a combined gasifier cookstove-TEG with a power output of 3.9 W at a temperature difference of approximately 60°C and a conversion efficiency of 2.01%. Montecucco *et al.* [106] developed a cookstove with a thermoelectric generator that is able to generate an average of 600 Wth and 27 Wel (42 Wel peak) during a 2-h long experiment in which the TEG efficiency is around 5%.

IV. *Future development*

The development of a gasifier cookstove has increased significantly in recent years since the biomass gasifier cookstove has better performance than other types of cookstoves. However, the stove requires electrical energy to power a fan on the stove, which causes additional energy cost. To encounter the electrical energy cost, thermoelectric generator technology has to be applied in the future development of a gasifier-thermoelectric biomass cookstove. Figure 4 presents a schematic diagram of a proposed biomass gasifier-thermoelectric (TEG) cookstove. TEG is attached to the outside wall of the burner, which utilizes heat loss from the burner to generate direct current electricity. The electricity is used to power the fan for supplying gasification air to the gasifier cookstove.

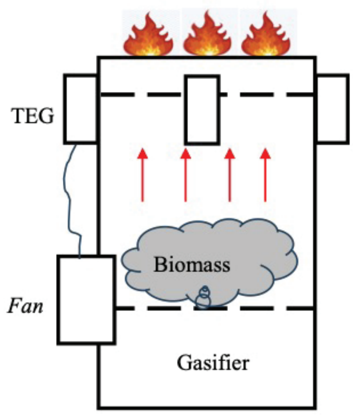

Figure 4: Schematic diagram of gasifier-TEG cookstove.

Figure 5 shows a schematic diagram of TEG where the hot side is attached to the heat source (i.e., the cookstove's wall). Heat flow creates a voltage through the Seebeck effect [107], [108]. The voltage (V) produced is directly related to the temperature difference (ΔT) between the hot and cold sides, following the formula: $V = \alpha \Delta T$, where α is the Seebeck coefficient [109], [110]. Electric power generated by the TEG can be used to power the fan of a gasifier cookstove. TEG has been applied successfully in waste heat recovery systems, such as on the exhaust pipe of an internal combustion engine [111] and a heat pipe [112]. However, TEG technology has not been used in a biomass gasifier cookstove so far.

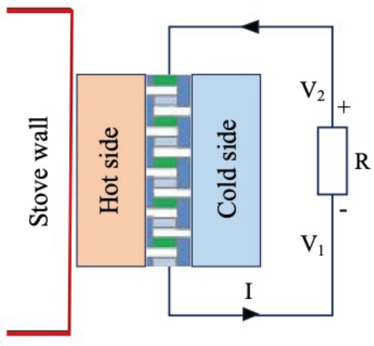

Figure 5: TEG for waste heat recovery.

V. Conclusion

Biomass cookstoves play an important role in supplying the world's heat demand for heating and cooking. A clean and eco-friendly cookstove has to be easily accessible to people, especially in rural villages of developing countries. Biomass gasification-based cookstove with attachment of TEG-powered fan is a promising technology to be applied for addressing the traditional cookstove problem.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author contribution

The contribution to the paper is as follows: Author 1 and Author 4: preparation of the final version of the manuscript; Author 2 and Author 3: preparation of a draft version of the manuscript

Data availability statement

The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

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