

# From waste to warmth: a recycled-component resistive starter that accelerates charcoal ignition and improves thermal efficiency

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## Abstract

The rising global energy costs have prompted many households, especially in rural areas, to seek alternative cooking methods to reduce expenses. In a developing country like Nigeria, charcoal, derived from fossil fuels, has become a popular choice due to its cost-effectiveness, faster-burning rate, and reduced emissions. However, the traditional method of igniting a charcoal fire requires specific expertise, which could result in severe environmental pollution if not available. In this study, we present the fabrication of an electric charcoal burner that harnesses the benefits of charcoal as a fuel source while eliminating the need for kerosene or other environmentally harmful agents. The fabricated electric charcoal burner utilises an electric power source to ignite the charcoal, providing a clean and efficient alternative to conventional ignition methods. The fabricated cooking device yielded an impressive average efficiency of 67.88%, surpassing the inefficiencies of conventional charcoal stoves. With an improved water boiling rate of 15.42 min/L, lower specific fuel consumption (27.53 g/L), average firepower of 0.88 kW, and a 1.79 g/min burning rate, this burner surpasses traditional methods. The affordability and versatility of the burner make it a practical choice for households seeking an alternative cooking method that is both cost-effective and eco-friendly.

**Keywords:** charcoal cooker, electric burner, pollution, energy, fossil fuel

## 1. Introduction

Cooking techniques encompass a variety of methods for applying heat to food to enhance its flavors and textures. These methods fall into several categories, including dry heat cooking, moist heat cooking, and combination cooking, which combines both dry and moist heat to prepare dishes. However, while the world grapples with energy price fluctuations, the situation has been exacerbated by the Russia-Ukraine conflict. This conflict has led to severe disruptions in energy supplies, resulting in soaring energy prices on a global scale. These price hikes have triggered global inflation and tighter monetary conditions, as documented by Dorothy (2022). Sub-Saharan African nations, such as Nigeria, have not been immune to these challenges. Both rural and urban communities in Nigeria are experiencing the effects of these energy price spikes. The inflation rate in Nigeria has surged to a record high of 26.7% as of September 2023, according to the National Bureau of Statistics (NBS, 2023).

Cooking gas costs in Nigeria have been increasing rapidly, and kerosene is no longer a preferred alternative due to its rising prices and health-related issues. Electric cooking, once considered a cost-effective solution, has also become less affordable due to the continuous surge in electricity tariffs (Kingsley, 2023). Consequently, many people have turned to charcoal as an alternative fuel for cooking. While this option is not without its challenges, particularly the discomfort caused by the initial smoke during the heating stage, it is increasingly viewed as a more environmentally friendly choice compared to burning firewood. The combustion of firewood generates harmful gases such as carbon monoxide, nitrogen oxides, and polyaromatic hydrocarbons, among others, which pose serious health risks to users (Petro et al., 2020). This burning process not only contributes to air pollution but has also been found to have detrimental health effects, especially for women and children, as revealed by research conducted by Felix & Gheewala (2011).

Charcoal is a solid fuel created through the process of carbonization (UN-FAO, 2015). Charcoal primarily consists of carbon with a fixed carbon content ranging from 50% to 95%. The ash content in charcoal can vary from approximately 0.5% to 5%, depending on factors such as wood species, contamination from earth and sand, and the presence of bark in the kiln. High-quality charcoal typically has an ash content of approximately 3% (FAO, 2020). Unlike firewood, charcoal predominantly transfers heat to the cooking vessel through radiation from the glowing fuel bed. At a glowing red heat, charcoal reacts with oxygen in the air to form colorless carbon monoxide gas, which subsequently burns with a blue flame using additional oxygen from the air to produce carbon dioxide gas. The heat generated by these reactions causes the charcoal to glow red and emit radiant heat energy, while the hot carbon dioxide gas exits the combustion zone. Ideally, most of the gas's heat is transferred by convection through direct physical contact with the cooking pot. As it releases heat, the gas temperature decreases, and it dissipates to the surroundings.

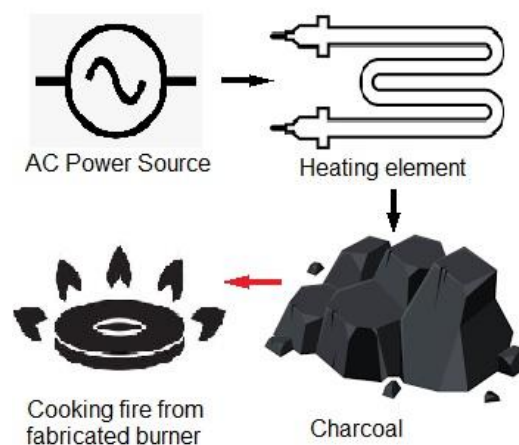
Despite the potential detrimental impact of charcoal to the environment and human health, charcoal stoves have been reported as better alternatives to firewood stoves as they burn more efficiently and cleanly (The World Bank, 2015). Efficient domestic charcoal-burning units are therefore designed with specific factors in mind. These include ensuring that the charcoal fuel bed is in close proximity to the pot it's heating, using refractory, insulating materials for the stove body, incorporating flue gas channels in the conical fire hole, utilizing a steel sheet grate with nail holes, and providing legs for the stove frame to maintain clearance between the stove block and the floor while collecting hot ash with a tray for added safety (FAO, 2020).

The quest for more efficient and environmentally friendly cooking solutions has become increasingly urgent due to rising energy costs and the detrimental health and environmental impacts associated with conventional cooking methods. Conventional electric stoves typically exhibit an average efficiency of approximately 49.1% (Muluken, 2020). Additionally, electric stoves have been shown to reduce energy consumption by approximately 95.7% when compared to traditional firewood stoves (Rasugu Ayub et al., 2021). This article is thus driven by the need to explore the development of an electric charcoal burner designed to enhance the efficiency of traditional charcoal usage. The proposed approach involves utilizing charcoal for cooking while employing an electric heater during the initial heating process. This innovative electric charcoal burner, which will be constructed as part of this study, is expected to not only address air pollution and health risks associated with charcoal stoves but also provide a more efficient and environmentally friendly cooking alternative.

## 2. Methodology

The functional block diagram of the electric charcoal burner is shown in Fig. 1. The system utilizes a recycled electric heating element and an ash collection tray, with power supplied by a 220 V alternating current (AC) source. The casing is fabricated from corrugated iron steel, which was subsequently painted to prevent corrosion of the cooker. This iron steel served as the main frame for the cooker, bent to a circular dimension measuring 500 mm (diameter) x 350 mm (length). Other components of the fabricated cooker include a pot stand, a grater, and a combustion chamber. The grate opens directly onto the ashtray and holds the charcoal being burnt. Holes are perforated on the grate to ensure that coal residues are directly deposited in the ash tray for easy disposal.

**Fig 1.** Operational block diagram of the fabricated electric charcoal burner



The operating principle of the fabricated device is governed by the principle of the heating effect of an electric heater, also known as Joule's law, given by the equation below (Britannica, 2022):

$$P = VI t = I^2 R t \quad (1)$$

Where P is the electric power loss, I is the electric current, V is the applied voltage (in this case, an AC voltage), R is the resistance of the heating element, and t is the time the current is allowed to flow. By Joule's heating principle, the amount of heat generated in an electrical system is proportional to the resistance of the heating element, provided the supply current and electrical resistance are kept constant.

To operate the fabricated electric charcoal burner, dry charcoal is obtained from local retailers in Ede, Osun State, Nigeria. The charcoal is then poured onto the grating surface while the heater is activated by switching on the 240 VAC power source. The electric current flows through the heating element, generating heat that directly raises the temperature of the charcoal. Depending on the size of the charcoal pieces used, combustion begins within a few seconds, and the charcoal ignites. Once the charcoal reaches a self-sustaining ignition level, the electric heating element is switched off. It is important to note that the primary function of the electric heating element is to ignite the charcoal, rather than being primarily used for cooking purposes.

The thermal efficiency of the fabricated electric charcoal burner was determined using the boiling water test method. This method can also be used to estimate water boiling rate, specific fuel consumption, fire power, and the burner rate of the fabricated electric charcoal burner (Berrueta et al., 2008; Petro et al., 2020). In this study, a standard aluminium pot of 3000 ml was used to boil 2000 ml of water to a final temperature of 95 °C. The thermal efficiency ( $\eta$ ) was determined as a ratio of energy consumed during heating and vaporizing of the water to the energy consumed by the burning charcoal, using the equation (Demissie et al., 2016; Visser, 2005):

$$\eta = \frac{((C_{pw} \times M_w) \times (T_2 - T_1)) + (H_v \times W_v)}{C_v \text{ of charcoal} \times V_{\text{charcoal}}} \times 100 \quad (2)$$

where  $C_{pw}$  is the specific heat capacity of water (4186 J/kg°C),  $M_w$  is the mass of boiled water (kg),  $T_2$  is the final temperature of the boiling water (°C),  $T_1$  is the initial temperature of the water (°C),  $H_v$  is the latent heat of evaporation of water (2260 J/g),  $W_v$  is the amount of water evaporated from the pot,  $C_v \text{ of charcoal}$  is the calorific value of charcoal fuel (MJ/kg), and  $V_{\text{charcoal}}$  is the volume of charcoal used (m<sup>3</sup>/h).

The water boiling rate ( $W_{BR}$ ) is the time taken for a given volume of water to reach its boiling point when subjected to a specific heat source. This time can be influenced by several factors, such as initial water temperature, quantity of water, power or heat input from the heat source, and environmental conditions. In this study, the water boiling rate is estimated using (Bantu et al., 2018):

$$W_{BR} \left( \frac{\text{min}}{L} \right) = \frac{\text{time to boil water (min)}}{\text{effective mass of boiled water (g)}} \times 1000 \quad (3)$$

Specific fuel consumption ( $S_{FC}$ ) is a measure of the amount of fuel required to raise 1 litre of water to its boiling point. It is also used to estimate the efficiency of an engine or power plant in terms of the quantity of fuel consumed when producing a certain amount of energy (Visser, 2005).  $S_{FC}$  indicates how efficiently a burner converts fuel into useful work or electricity, i.e., the lower the  $S_{FC}$  value, the more fuel-efficient the burner or engine. In this study, the  $S_{FC}$  is determined using (Bantu et al., 2018; Cookstoves, 2014; Petro et al., 2020):

$$S_{FC} (g/L) = \frac{\text{charcoal fuel consumed (g)}}{\text{effective mass of boiled water (g)}} \times 1000 \quad (4)$$

The firepower ( $F_p$ ) of a burner refers to the capacity of the burner to generate heat. It is also the proportion of fuel energy utilized by the burner per unit time. The firepower of a burner is an essential consideration in various applications, such as industrial processes, heating systems, and cooking appliances. It determines how quickly a burner can generate heat and, subsequently, how efficiently it can perform its intended function. In cooking appliances, for instance, a high-powered burner can quickly bring water to a boil or provide intense heat for cooking. When selecting a burner for a specific application, it's important to consider the required firepower to ensure that it can meet the heating or cooking needs effectively and efficiently. In this study, the firepower of the fabricated electric charcoal burner is given by (Bantu et al., 2018; Berrueta et al., 2008; Petro et al., 2020):

$$F_p = \frac{\text{charcoal fuel consumed (g)} \times \text{lower – heating – value (J/g)}}{\text{time to boil water (min)} \times 60} \tag{5}$$

The burning rate ( $B_R$ ) of a burner is the rate at which fuel is consumed and converted into heat energy by the burner. For example, in a cooking appliance, the burning rate of a gas burner affects how fast food can be cooked or how quickly water can be brought to a boil. The boiling rate can vary depending on several factors, including the type of fuel, burner design, and the specific application. The boiling rate in this study is estimated using (Petro et al., 2020):

$$B_R = \frac{\text{fuel consumed (g)}}{\text{time to boil water (min)}} \tag{6}$$

### 3. Results and Discussions

The electric charcoal burner fabricated in this study is presented in Fig. 2. For all the charcoal types used as fuel, the combustion time ranged between 30 seconds and 120 seconds. This difference is due primarily to the supply voltage, which fluctuates between 180 VAC and 220 VAC. Optimum performance was obtained at 220 VAC supply voltage. The efficiency of a charcoal burner is determined by the quantity of heat transferred from the charcoal to the object undergoing heating, and the utilization of appropriately designed combustion equipment (FAO, 2020). Factors such as the heat output during cooking, the quantity of fuel burned during the cooking process, and the frequency of refuelling the burner can impact the efficiency measurement procedure (Carol, 2017).

**Fig 2.** Electric charcoal burner fabricated in this study



The thermal efficiency of the fabricated electric charcoal burner is presented in Table 1. Compared to charcoal stoves with reported efficiencies of less than 10%, where approximately 90% of the heat is reportedly lost during combustion (Energy-education, 2018), the electric charcoal burner fabricated in this study exhibits an enhanced average efficiency of 67.88%. This improved efficiency is primarily attributed to a significant reduction in the time required for the charcoal to reach the desired temperature. Local charcoal stoves, as reported by Boynton (2015), can take up to thirty minutes to heat up, resulting in reduced efficiency. In contrast, the electric charcoal burner fabricated in this study reaches the desired temperature in a maximum of 120 seconds, thus minimizing the emission of black soot during the heating process. This substantial reduction in soot production not only contributes to improved charcoal efficiency but also reduces overall cooking time. Similar results were obtained by Chu et al. (2019), Jianfei et al. (2021), and Qi et al. (2021).

**Table 1.** Thermal efficiency estimation of the fabricated electric charcoal burner

| Performance index               | TP-1  | TP-2  | TP-3  | TP-4  | Mean  | STD  |
|---------------------------------|-------|-------|-------|-------|-------|------|
| Thermal efficiency (%)          | 60.11 | 67.87 | 78.56 | 64.98 | 67.88 | 7.81 |
| Water boiling rate (min/L)      | 15.44 | 16.35 | 14.81 | 15.08 | 15.42 | 0.67 |
| Specific fuel consumption (g/L) | 28.25 | 25.80 | 25.56 | 30.52 | 27.53 | 2.33 |

|                      |      |      |      |      |      |      |
|----------------------|------|------|------|------|------|------|
| Firepower (kW)       | 0.90 | 0.78 | 0.85 | 1.00 | 0.88 | 0.09 |
| Burning rate (g/min) | 1.83 | 1.58 | 1.73 | 2.02 | 1.79 | 0.19 |

The results obtained from Table 1 reveal an average water boiling rate of 15.42 min/L, which surpasses the rate of 14.8 min/L reported by Bantu et al. (2018) in a burner constructed from high-density heated rocks. It is important to note, however, that our results do not account for potential heat loss in the electric charcoal oven, which lacked insulation, and may be influenced by various environmental factors. The specific fuel consumption (SFC) of the fabricated electric charcoal burner averaged 27.53 g/L, significantly lower than the 47 g/L and 245.34 g/L reported by Bantu et al. (2018) and Petro et al. (2020), respectively. This low SFC value plays a crucial role in enhancing the overall thermal efficiency of the fabricated burner, signifying its fuel-efficient performance.

The average firepower obtained in this study is 0.88 kW, which is higher than the 0.18 kW reported by Petro et al. (2020) but lower than the 1.57 kW obtained by Bantu et al. (2018). Factors influencing a burner's firepower include fuel type, burner size, combustion efficiency, operating pressure, air-to-fuel ratio, and adapted burner technology, leading to variations in firepower values. Notably, different burner technologies employed in the studies investigated could contribute to these variations. Additionally, the average burning rate of the fabricated burner is 1.79 g/min, representing a 52% improvement over the value obtained by Petro et al. (2020). This result suggests that the electric charcoal burner created in this study will quickly generate heat as the charcoal is consumed rapidly, a typical characteristic of charcoal-based burners. Such burners ignite fast and provide ample heat for cooking activities.

The electric charcoal burner presented in this study successfully addresses a significant concern related to health and environmental issues associated with the use of charcoal as a fuel source. According to The World Bank (2015), the health problems linked to charcoal burning, primarily due to the smoke it generates, have led to an increased prevalence of conditions such as pneumonia, stroke, heart disease, and lung cancer (The World Health Organization, 2015). However, from the results presented in Table 1, this study achieves faster charcoal combustion by employing an electric heating element, effectively mitigating health concerns and their consequences for users. This is achieved by minimizing or virtually eliminating the production of soot during the startup process, enhancing the overall safety of the charcoal burner and well-being of users.

## 4. Conclusion

In this study, an electric charcoal burner has been successfully fabricated using recycled materials. This innovative appliance represents a significant advancement in cooking technology, particularly in addressing the challenges associated with traditional charcoal stoves. Notably, it significantly reduces the time required for charcoal to reach the desired temperature, with heating times ranging from as little as 30 seconds to a maximum of 120 seconds, contingent on the supply voltage. Optimal performance was achieved at 220 VAC.

Furthermore, the fabricated electric charcoal burner exhibited a remarkable increase in efficiency, achieving an average efficiency of 67.88%, in stark contrast to the typically low efficiency rates of less than 10% associated with traditional charcoal stoves. This enhancement in efficiency is attributed to the reduced heating time and more efficient combustion, resulting in a significant reduction in the production of black soot during the heating process. By utilizing an electric heating element for faster charcoal combustion and minimizing soot emissions during startup, the fabricated electric charcoal burner provides a safer and healthier cooking alternative, effectively addressing environmental and health concerns associated with traditional charcoal stoves.

In addition to its functional benefits, the fabricated electric charcoal burner boasts affordability in construction, efficient design, and portability. It offers a cost-effective alternative to existing, often expensive, commercial variants while delivering comparable performance. This research contributes to the development of sustainable and accessible cooking solutions, emphasizing both efficiency and environmental and health considerations, thus making it a promising addition to the realm of modern cooking technology.

## Declarations

**Data availability:** Data will be made available upon reasonable request.

**Funding:** This study received no funding.

**Competing interests:** The authors declare that they have no known competing or financial interests.

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