



# Development of a Multifunctional Thermal Processing Machine for Baking, Roasting and Drying with Energy Consumption Analysis

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## ABSTRACT

Limited access to efficient and versatile thermal processing equipment constrains small and medium-scale bakeries in developing countries, necessitating the design of a multifunctional thermal processing machine capable of supporting multiple heating methods and uniform heat distribution. This study aims to design, fabricate, and evaluate a multifunctional thermal processing machine capable of roasting, baking, and drying, utilizing electricity, gas, and charcoal as energy sources. Gas heating demonstrated the highest efficiency for high-temperature operations, reaching 200 °C in 25 mins with a maximum chamber temperature of 298 °C and energy consumption of 5.04–13.0 MJ. Electrical heating consumed 16.82–22.5 MJ but provided superior temperature stability and control, effectively reducing date fruit moisture from 29% to 17.24% over four hours at 70 °C. Charcoal heating was the least energy-efficient, requiring up to 77.0 MJ, although it yielded superior sensory attributes. Therefore, the machine's versatility and performance across multiple energy sources highlight its potential as a scalable thermal processing solution for food enterprises in regions with variable energy availability.

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## INTRODUCTION

Thermal processing is a foundational operation in food transformation and preservation, widely employed to improve the safety, quality, and shelf life of food products. The most common thermal food processing are baking, roasting, and drying, where each relies on controlled heat and mass transfer to achieve desirable sensory, microbiological, and physicochemical properties (Sanusi *et al.*, 2020). However, conventional food processing systems are often single-function, energy-intensive, and lack the adaptability required in modern and resource-constrained environments. This is particularly challenging for small and medium-scale processors in developing economies

who must navigate fuel availability, rising energy costs, and the need for multipurpose equipment.

Addressing these challenges requires the development of a multifunctional thermal processing system that integrates baking, roasting, and drying capabilities within a single unit, a solution beneficiary to small and medium-scale enterprises (SMEs) in agri-food sectors, which often face infrastructural and economic limitations. Such systems are not limited to space and cost savings but also enhance process continuity, energy efficiency, and operational versatility (Sumbodo *et al.*, 2022; Gbabo *et al.*, 2024). Energy consumption remains a major concern in thermal food processing, directly impacting operational cost and environmental

sustainability. A similar important advancement is the incorporation of multiple heating sources, namely electricity, gas, and charcoal, to ensure uninterrupted operation regardless of energy supply fluctuations. This multi-powered flexibility offers a critical advantage in low and middle-income countries (LMICs), where access to stable electricity and clean fuels is inconsistent (Adegbola et al., 2021).

The study aims to design, develop, and evaluate a multifunctional thermal processing machine capable of executing baking, roasting, and drying operations, powered by three interchangeable heating sources: electricity, gas, and charcoal. The equipment performance evaluation was conducted on food products for each operation: scone snacks for baking, wet dates for drying, and plantain for roasting. Parameters evaluated are thermal efficiency, product-specific energy consumption, and processing performance under each energy mode. Furthermore, existing literature provides minimal data on the comparative energy consumption of various food products under different thermal operations and heating sources. This research contributes to the ongoing global effort to develop sustainable, scalable, and inclusive food processing technologies, especially those tailored to the unique infrastructural and economic contexts of low- and middle-income countries.

## MATERIALS AND METHODS

### Machine design and fabrication

Figure 1 depicts the orthographic projection of the multifunctional thermal processing machine. The primary heat sources integrated into the design are electricity, liquefied petroleum gas (LPG), and charcoal. The machine's structural frame was constructed from mild steel for durability, while the internal processing chamber, measuring 941 mm in height, 534 mm in width, and 572 mm in length, was fabricated from AISI 304 stainless steel to ensure

food-grade compliance, corrosion resistance, and effective heat retention. The chamber was insulated with fiber wool to minimize heat loss and enhance thermal efficiency. A hinged door fitted with a heat-resistant borosilicate glass panel allowing for visual monitoring of the process. An escape valve was fitted at the top to release excess pressure and moisture during drying operations. For enhanced mobility, castor wheels are attached to the base.

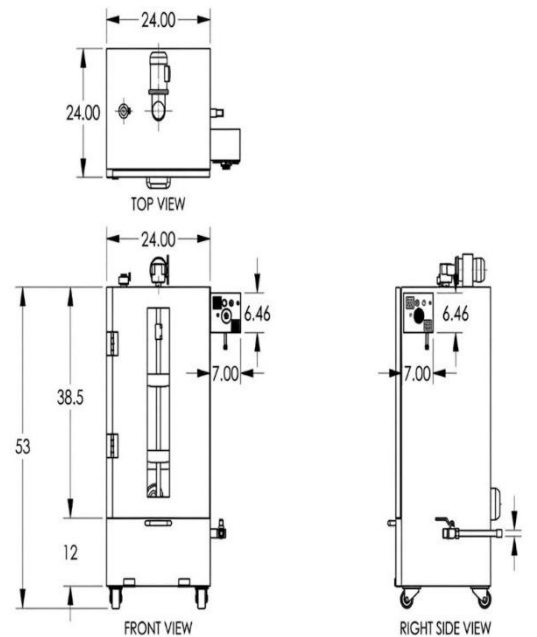


Figure 1: Orthographic Projection of the Multifunctional Thermal Machine (All measurements are in inches)

The heating systems of the machine were configured with three distinct heat sources to ensure versatility. The electric heating system comprise of two heating elements with a combined capacity of 3 kW. Temperature control for this system is managed by a temperature controller and a high-capacity relay switch (contactor) to ensure precise and stable temperature regulation. In addition, an LPG burner with a high-power output, was incorporated for gas heating, with the gas flow and heat intensity being regulated via a manual control valve. A dedicated chamber was positioned beneath the main processing chamber to accommodate charcoal pot

for solid fuel alternative. Beyond the heating systems, the machine's design also included a DC motor to drive a rotating rod with two stainless steel bowls, which provided uniform heat exposure to the products. To further enhance even heat distribution, a hot air blower was integrated to circulate hot air within the chamber.

**Design considerations**

The design of the machine was guided by several factors such as, thermal efficiency, sanitary and hygienic properties, ease of operation, versatility (multiple heating sources), and cost and material availability. Figure 2 depicts the exploded and isometric views of the multifunctional thermal processing machine.

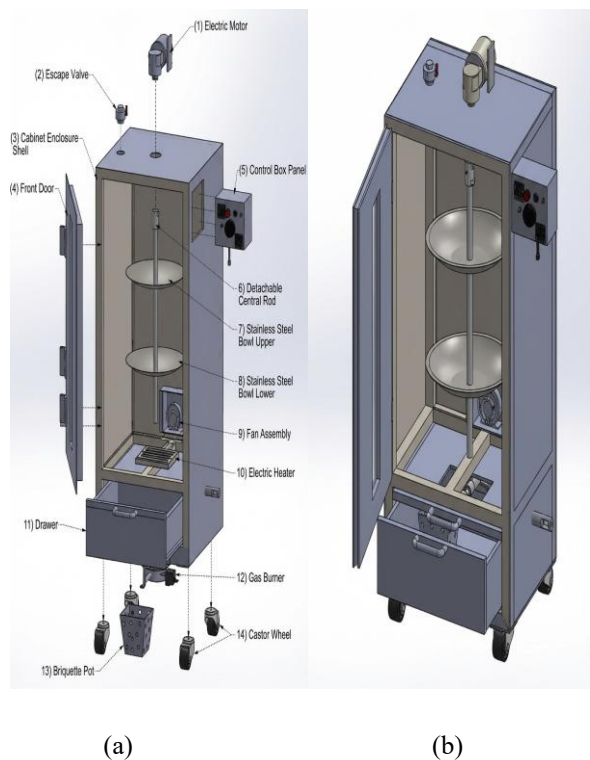


Figure 2: Exploded (a) and Isometric (b) views of the Multifunctional Thermal Machine

**Materials for construction**

The materials used for the construction of the multifunctional thermal processing machine include: Mild Steel (for the frame), AISI 304 Stainless Steel (inner chamber and food bowls),

Heat-resistant glass, Fasteners (rivet pins and welding electrodes), and Insulation (fiber wool).

**Design calculations**

**Processing chamber height**

Machine Height (MH) = 1245 mm, Machine Length (ML) = 610 mm, Machine Width (MW) = 610 mm, Charcoal Chamber Height (CCH) = 304 mm

$$CH = MH - CCH \tag{1}$$

Where CH is the chamber height

Therefore;  $CH = MH - CCH = 941 \text{ mm}$

**Processing chamber width**

Wall thickness (WT) = 38mm, Width of the Processing chamber is calculated as

$$CW = MW - 2WT \tag{2}$$

Where CW is the chamber width

Therefore,  $CW = 610 - (38 \times 2) = 534 \text{ mm}$

**Processing chamber length**

The length of the processing chamber was calculated using Eq. 3

$$CL = ML - WT \tag{3}$$

Where CL is chamber length

Therefore,  $CL = 610 - (38 \times 2) = 534 \text{ mm}$

**Surface area of the processing chamber**

The total surface area of the processing chamber is essential for determining heat transfer and insulation needs. For a rectangular chamber, the surface area (A) is calculated using Eq. 4.

$$A = 2(CL \times CW + CL \times CH + CW \times CH) \tag{4}$$

Total surface area,  $A = 2.58 \text{ m}^2$ .

**Volume of the processing chamber**

The volume of the chamber (V) was calculated using Eq. 5 as describe by Sanusi et al., (2020).

$$V = CL \times CW \times CH \tag{5}$$

Thus, the volume of the chamber  $V = 0.268 \text{ m}^3$

**Capacity of the electric heating element**

The heat required was calculated using Eq. 6 as described by Sanusi *et al.* (2020)

$$Q_H = M_b \times C_b \times T_d \tag{6}$$

Where  $M_b$  is mass of bread,  $C_b$  is the specific heat capacity of bread and  $T_d$  is temperature difference.

Mass of scone is 0.25 kg; Specific heat capacity of dough is 2890 J kg<sup>-1</sup> K<sup>-1</sup> according to Sanusi *et al.* (2020); average baking temperature in oven was 200 °C ≡ 473.15 K; oven room temperature is 27 °C ≡ 300.15 K. Therefore, the quantity of heat required to bake 20 scone per batch,  $Q_H$  was calculated as 2,499,850 Joules.

Power (P) of the heating element was calculated using Eq. 7 (Okafor, 2014; Sanusi *et al.* 2020)

$$P = \frac{E}{T} \tag{7}$$

where  $P$  is the power of the electric heating element,  $E$  is the energy and  $T$  is average processing time per dough batch.

Assuming the average processing time per scone dough batch is 20 min, thus, from Eq. (6) the quantity of heat supplied to the oven chamber is 2,499,850 J. According to Sanusi *et al.* (2020), energy required to gelatinize starch in a dough is 1.2 J/g, therefore the heat transfer to the dough is equivalent to;

$$HD = ERG \times Q_H \tag{8}$$

where  $HD$  is heat transfer to the dough and  $ERG$  is energy required to gelatinize the starch in scone dough.

Therefore,  $HD$  was calculated as 2,999,820 J.

Thus, from Eq. 7;  $P = 2,499.85 W = 2.5 kW$

Thus, power of electrical heating element of 3 kW was selected.

The resistance of the heating element and the current required were calculated using Eq. 9 and Eq. 10 (Anyakoha, 2016).

$$P = \frac{V^2}{R} \tag{9}$$

where  $V$  is voltage supply in Nigeria and  $R$  is the electrical resistance ( $\Omega$ ).

Thus from Eq. 9, the resistance of the heating element,  $R$ , is 17.6  $\Omega$ , given the values of 230 V and 3000W for  $V$  and  $P$  respectively.

For current  $I$ ,

$$I = \frac{P}{V} \tag{10}$$

The current required for the machine was determined to be 13 A.

**Air flow rate of the blower**

The airflow rate was calculated using the formula:

$$AF = U \times V \tag{11}$$

Where  $U$  is air change (m<sup>3</sup>min<sup>-1</sup>) and  $V$  is volume of the machine.

An air change of 7 m<sup>3</sup>min<sup>-1</sup> was assumed since the value is within the recommended for thermal processing machine design. Given the values of 7 m<sup>3</sup>min<sup>-1</sup> and 0.28743 m<sup>3</sup> for  $U$  and  $V$  respectively, the airflow rate ( $AF$ ) is 2.01 cfm.

**Heat loss through the walls**

Fourier’s first law of heat transfer was used to calculate heat loss through the walls (Eq. 2.9), considering that the inner temperature is 70°C, while the outside is at room temperature of 30°C.

$$q_{loss} = \frac{T_2 - T_1}{\left( \frac{\Delta x_{s1}}{k_s A} + \frac{\Delta x_w}{k_w A} + \frac{\Delta x_{s2}}{k_s A} \right)} \tag{12}$$

Where  $q_{loss}$  = quantity of heat,  $\Delta x_s$  = thickness of mild steel,  $\Delta x_w$  = thickness of fiber wool,  $k_s$  = thermal conductivity of mild steel,  $k_w$  = thermal

conductivity of fiber wool insulation, A = area of the wall,  $T_2$  = temperature of the roaster,  $T_1$  = temperature of the surrounding environment

Given the values of 0.005 m, 0.038 m, 16 W/m.K, 0.042 W/m.K, 2.7 m<sup>2</sup>, 70°C and 30°C for  $\Delta x_s$ ,  $\Delta x_w$ ,  $k_s$ ,  $k_w$ , A,  $T_2$  and  $T_1$  respectively. Therefore, the heat loss ( $q_{loss}$ ), is approximately 119.3 W (or 0.119 KW). Thus, the insulation is effective in minimizing heat loss.

**Selection of electric motor**

The rotational speed and power consumption was used in the selection of the motor. The machine uses 3 amps and a 12 V electric motor. To determine rotational speed Eq. (13) was used (McCable et al., 1985; Sanusi et al., 2020).

$$mgh = \frac{1}{2} mv^2 \tag{13}$$

where,  $m$  is mass of load on the rotor (g),  $g$  is acceleration due to gravity (9.8 ms<sup>-2</sup>),  $h$  is height of load from the rotor (0.3 m)  $v$  is speed of the rotor (ms<sup>-1</sup>).

From Eq. (13),

$$v = \sqrt{2gh} \tag{14}$$

Therefore, the speed of the motor was 4.2 ms<sup>-1</sup>

The motor power (P) consumption was determined using Eq. 15 (Kirschen et al., 1985).

$$P = VI\sqrt{3} \tag{15}$$

The motor power consumption was calculated as 172.5 W ≈ 0.173 kW, given the values of 12 V, 8.3 A for  $V$  and  $I$  respectively. Therefore, a motor with power consumption of 0.23 Hp was selected.

**Electrical energy consumption (EEC)**

The electrical energy consumption of the multifunctional thermal processing machine was estimated using Eq. 16 (Sanusi et al., 2023).

$$EEC = EEC_b + EEC_h \tag{16}$$

Where  $EEC_b$  is electrical energy consumed by the blower (single phase blower) and  $EEC_h$  is electrical energy consumed by electric heating element and electric motor.  $EEC_b$  was estimated using Eq. 17 while  $EEC_h$  was estimated using Eq. 18.

$$EEC_b = \sqrt{(VI \cos \phi)} \times t \tag{17}$$

$$EEC_b = P_{osm} + P_b \times t \tag{18}$$

Where  $V$  is the line voltage,  $I$  is the line current,  $\cos \phi$  is the power factor,  $t$  is the operating time (h),  $P_b$  is the electric heating element rated power, and  $P_{osm}$  is the power rating of the electric motor.

**Energy consumption using gas or charcoal**

The energy consumption patterns during heating for gas and charcoal combustion heating modes were estimated by fitting data of labour, LPG combustion and charcoal combustion into Eq. 19 (Sanusi and Akinoso, 2021).

$$E_{gc} = (0.75N \times 0.016t) + (Qf \times Cf) \tag{19}$$

$E_{gc}$  is the energy consumption for heating using gas and charcoal combustion,  $N$  represents the average power in the tropical region of a male labour (0.75 MJ/h),  $t$  is time taken to accomplish a unit operation (h),  $Qf$  is the quantity of the fuel (LPG) consumed and  $Cf$  is the constant of proportionality which represents the calorific value of Liquefied Petroleum Gas (LPG) or charcoal.

**Thermal efficiency**

The thermal efficiency ( $\eta$ ) of the machine was evaluated using Eq. 20.

$$\eta = \frac{Q_{useful}}{Q_{in}} \times 100\% \tag{20}$$

Where  $Q_{useful}$  is the useful heat gained by the product being processed.

$$Q_{useful} = m_p \times c_p \times \Delta T + m_w \times L \tag{21}$$

Where  $m_p$  = mass of product (kg),  $c_p$  = specific heat capacity of the product (kJ/kgK),  $\Delta T$  = temperature change of the product,  $m_w$  = mass of water removed,  $L$  = latent heat of vaporization.

$Q_{in}$  is the total heat energy supplied by the heating source.

### **Product preparation**

Scones were prepared following a special formulation consisting of flour, butter, sugar, eggs and baking powder, and were portioned into 250 g samples. Dried dates were cleaned, soaked for 12hrs to ensure uniform hydration, pitted to ensure even drying and then processed in 2 kg batches (1 kg per bowl). Plantains were cleaned, peeled and processed at 5 fingers per bowl. All samples were prepared at ambient conditions prior to processing to ensure consistent thermal behavior.

### **Experimental procedures**

Each product was processed using the multifunctional thermal processing machine, however, while baking and roasting processes were powered by the three alternative heat sources: electricity, gas, and charcoal, economic considerations preclude the use of certain heating sources such as gas and charcoal for drying applications, hence only electricity was used. Scones were baked at 160 °C until desired quality is reached approximately (20 mins), dates were dried at 70 °C until their moisture content reached 15 – 17% (wet basis), while whole peeled plantains were roasted at 180 °C. Temperature performance was assessed by monitoring chamber temperature using a K-type thermocouple placed in the processing chamber. Baking and roasting experiments were repeated three times using the three heat sources while drying experiment was done once in comparison with a standard rotary dryer.

### **Sensory evaluation of baked scone and roasted plantain using the multifunctional thermal machine**

The sensory attributes of the scone product were assessed based on colour, aroma, taste, texture and overall acceptability of the scone produced using the three heating modes. Samples were labelled A, B and C on scone products to represent electricity, gas and charcoal respectively. The sensory evaluation was done using the 9-point hedonic scale with 30 semi-trained panelists.

### **Analyzing the moisture content of the dates samples dried with the multifunctional thermal machine**

To assess the drying performance of the multifunctional thermal processing machine, the moisture content of date fruit samples was analyzed using a DHS series moisture meter (DHS16-A, China) due to its speed and accuracy. Three different samples were evaluated; Where, sample A was the undried date sample, sample B was the sample dried with the multifunctional thermal processing machine, and sample C was the sample dried with the oscillatory dryer. Each sample was subjected to the same drying conditions for consistency. An initial weight of 10 g, a preset temperature of 120°C and analyzing time of 15 mins was set for all samples (Table 1).

## **RESULTS AND DISCUSSION**

### **General evaluation of the multifunctional thermal processing (MTP) machine**

Figure 3 shows the pictorial representation of the multifunctional thermal processing machine. Performance evaluation of the machine was conducted to assess the functionality of different operation modes (roasting, drying, and baking). The test verified its efficiency and safe operations across all modes. The evaluation encompassed the

following key components: Electric heating element, roasting, drying or baking chamber, temperature sensor and controller, electric blower, Charcoal chamber, and gas burner. Components were tested both individually and in integrated operation. The control box effectively regulated and distributed power to operational elements, including heating systems and sensors. The temperature sensor, integrated with a digital controller, consistently provided accurate real-time temperature readings (°C).

**Table 1: Conditions for analysing moisture content of date fruit using DHS moisture meter**

Condition	Undried date sample (A)	MTP machine sample (B)	Oscillatory dryer sample (C)
Ambient temperature (°C)	42	44	43
Preset temperature (°C)	120	120	120
Time of analysis (min)	15	15	15
Initial weight (g)	10.09	10.04	10.01
Final weight (g)	7.12	8.31	8.98
Moisture content (%)	29.41	17.24	12.16

In a comparative analysis of thermal performance across the three heat sources, the machine's thermal generation capabilities were evaluated using electricity, gas, and charcoal as primary heat sources. Performance metrics were quantified through controlled experiments measuring Time-to-target temperature, Maximum temperature, temperature stability ( $\pm^{\circ}\text{C}$  variance), and operational suitability for each processing operations. Gas and electricity achieved the target temperature of 200 °C in 25 and 50 mins,

respectively. On the other hand, when using charcoal as the heat source, the machine could only reach a temperature of 165°C after one hour (Figure 4).



Figure 3: The Multifunctional Thermal Processing Machine

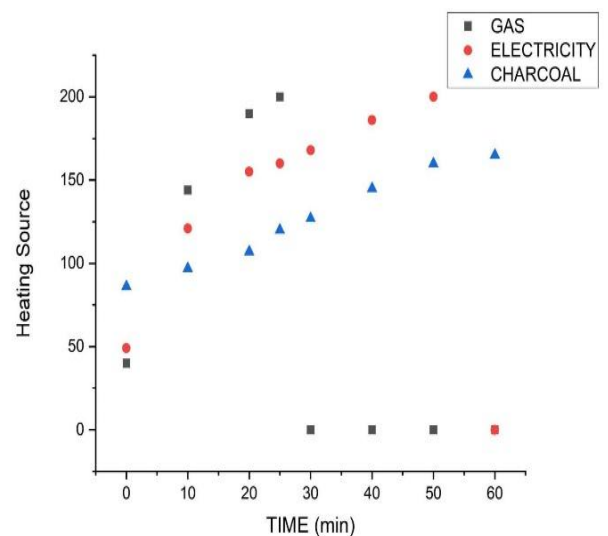


Figure 4: Effect of heating source on processing time

**Influence of heat source on maximum temperature in the processing chamber**

The heating source critically influences maximum temperatures and operational control in the processing chamber of the MTP machine. Gas combustion achieved the highest temperature of

298°C, though its controllability challenges and safety requirements may complicate precise thermal management. Electricity delivered an impressive heating temperature up to 200°C, with superior controllability and energy efficiency, enabling stable temperature regulation. Charcoal yielded the lowest output (189°C) while exhibiting poor controllability and inconsistent combustion characteristics, rendering it operationally impractical for precision applications. These results indicate that gas-based systems provide substantially superior thermal efficiency under the tested conditions, suggesting their preferential selection for applications requiring high-temperature performance, while electricity offers optimal balance for controlled processes. Charcoal, on the other hand should only be used as an alternative in situation where gas or electricity is unavailable (See Figure 5).

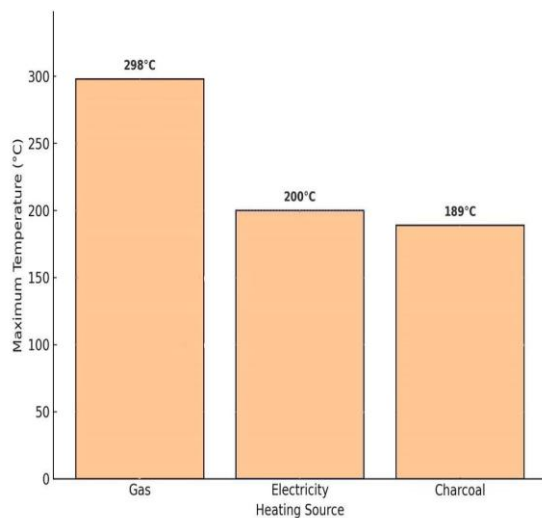


Figure 5: Effect of heating source on the maximum temperature

### Baking time of the multifunctional thermal processing machine

The baking time for the dough is determined when the baked dough attained the desired taste, colour, texture and moisture content such as a well-developed golden-brown crust with a distinct

structural crunch (Henry and Kettlewell, 2012). Electricity required 51 mins at 160 °C to fully bake the dough to desired specifications. This could be due to the fact that a heat blower was installed into the baking compartment of the machine increasing the rate of baking, and causing uniform circulation of heat thereby decreasing the baking time. Electric heating tends to give a more uniform progressive heating compared to gas (Rana *et al.*, 2023). Gas took 60 min for the dough to achieve the desired baking result. While using charcoal as the heating source took 90 min for the product to develop crunchy and golden-brown crust.. Similar result was reported by Alimasunya *et al.* (2016), that using charcoal as a source of energy during baking may lead to longer baking time.

### Roasting time of the multifunctional thermal processing machine

During roasting operation of plantain, gas took the shortest time, reaching the target roast qualities in roughly 65 mins, while electricity followed closely, completing the process in about 80 mins. Charcoal was the slowest, averaging 110 mins to achieve the desired result. These results highlight that gas and electricity provide a more rapid and consistent roasting process, making them ideal for time sensitive applications. One major factor that affected the roasting was temperature. This result corroborates with the findings of Abankwa *et al.* (2025), that the difficulty of controlling the temperature of a roaster depends on the heat source employed for the roaster. The use of charcoal generates a less efficiency due to the difficulty in regulating the temperature of heat produced.

### Drying time of the multifunctional thermal processing machine

Drying of date fruits was done at a temperature of 70°C and the multifunctional processing machine took 4 hours to reduce the moisture content of pitted

date fruits from 29% to 17% (wet basis). A similar result was reported by Al-Awaadh *et al.* (2015), stating that in order to prevent changes in colour and texture of the date fruit, the range of drying temperature of date fruit should be 60 - 70°C.

**Energy consumption and efficiency**

**Electrical energy consumption**

The electrical energy consumption (*EEC*) of the thermal processing system was calculated as the sum of the energy consumed by the blower (*EEC<sub>b</sub>*) and the combined energy consumed by the heating element and DC motor (*EEC<sub>h</sub>*). With a blower rated at 1500W, heating element of 3kW and DC motor of 172.5 W, baking of scone snacks for 51 mins consumed 14.3 MJ of electrical energy. 80 mins of roasting operation consumed 22.5 MJ of energy (Figure 6).

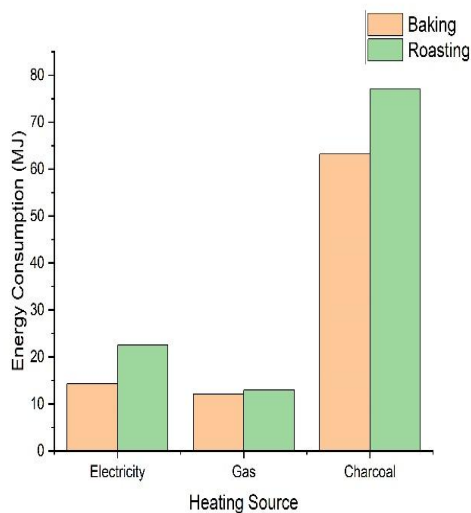


Figure 6: Effect of heating source on energy consumption during baking and roasting of scone

The drying period took 4 hours with total energy consumption of 67.28MJ compared to a standard rotary oven whose total energy consumption was 36.3 MJ (Figure 7). The difference in the drying energy consumption could be attributed to less time consumed for drying and increase in movement and circulation of air. This result corroborates with the findings of Akan and Özkan (2020), who reported

that the drying efficiency could be improved with an oscillatory dryer thereby reducing the drying time compared to a stationary dryer. The energy distribution reveals that the heating element was the dominant consumer of energy, accounting for the highest percentage of the total *EEC*. The blower contributed significantly to the overall load, while the energy drawn by the DC motor was negligible, representing only a fraction of the total energy consumption. Also, the study shows that electrical energy consumption is a factor of time as longer time results to increase in electrical energy consumption.

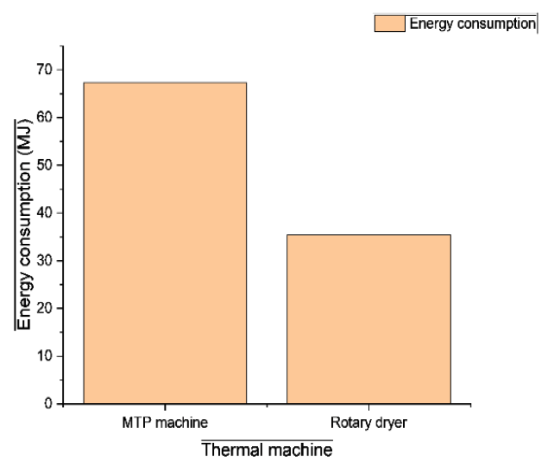


Figure 7: Electric energy consumption between MTP machine and Rotary dryer during drying of dates

**Gas and charcoal energy consumption**

The energy consumption for the heating processes, encompassing both fuel energy and direct labor input, was evaluated for liquefied petroleum gas (LPG) and charcoal. The calorific values *C<sub>f</sub>* used for the evaluation were 50.35 MJ for LPG as reported by Sanusi *et al.*, (2022), and 30.09 MJ for charcoal (Adamu *et al.*, 2018).

From Figure 6, the baking operation energy consumption for heating using gas was calculated to be 12.1 MJ while, charcoal heating resulted in a significantly higher energy consumption of 63.2

MJ. The roasting system powered by gas also recorded a low energy consumption totaling 13.0 MJ, while charcoal powered roasting exhibited the highest energy consumption, measured at 77.0 MJ, making it the least efficient option under evaluation. This result aligns with the findings of Dębowski *et al.* (2021), that the energy consumption of gas is lower compared to charcoal as a result of difference in chemical composition which cause variation in the combustion.

**Sensory evaluation of baked scone snacks**

Table 2 presents the sensory evaluation results for the baked scones, indicating that overall acceptability scores across the three heating sources ranged from 6.7 to 8.5 as evaluated by the panelists. Charcoal-baked scones (sample C) were rated the highest overall ( $8.50 \pm 0.58$ ), significantly preferred over the others, producing the best results in terms of sensory attributes, better colour, aroma, taste, texture and overall acceptability than samples A and B. This could be due to the smoke generated from

the charcoal which tends to add to the flavor of the scone product thereby increasing the overall sensory properties of the scone. He *et al.* (2024) highlighted in a study that charcoal heating can largely influence the aroma of baked products. Sample B had the lowest score across most attributes, possibly due to uneven heat distribution or weaker top browning typical of some gas ovens. The colour of the scone ranged between 7.25 and 7.75 for sample A and C, with a very close range, this slight difference could be due to the heat gun aiding the flow and distribution of heat inside the baking chamber when using electric heating.

**Sensory evaluation of roasted plantain**

Figure 8 shows the graphical illustration of the sensorial evaluation of roasted plantain produced with the multifunctional thermal processing machine. Charcoal-roasted plantains achieved the highest rating for colour (8.2), yielding a rich, golden-brown exterior.

**Table 2 Sensory attributes of scone**

S/N	Colour	Aroma	Taste	Texture	Overall acceptability
A	7.25±0.50 <sup>ab</sup>	7.50±1.00 <sup>ab</sup>	8.00±0.82 <sup>ab</sup>	7.50±0.58 <sup>ab</sup>	7.75±0.50 <sup>a</sup>
B	6.50±0.58 <sup>b</sup>	6.50±0.58 <sup>b</sup>	7.25±0.96 <sup>b</sup>	6.75±0.50 <sup>b</sup>	6.75±0.50 <sup>b</sup>
C	7.75±0.50 <sup>a</sup>	8.00±0.00 <sup>a</sup>	9.00±0.00 <sup>a</sup>	8.25±0.95 <sup>a</sup>	8.50±0.58 <sup>a</sup>

*A is Electricity baked scone, B is gas baked scone and C is charcoal baked scone*

This is attributed to the maillard reaction, a chemical interaction between amino acids and reducing sugars at high temperatures (typically 140 –165°C, optimal for roasting), producing melanoidins responsible for the brown color and complex flavors in roasted foods (Nooshkam *et al.*, 2019). In terms of aroma and taste, both charcoal and electric roasting were rated highly by the panelist, with aroma scores approximately 7.9 and 8.1 for charcoal and electric, respectively, and taste averaging about 8.3 (charcoal) and 8.5 (electric). Electric roasting led in taste with a score of 8.2. Gas-roasted plantains

delivered satisfactory results across all sensory attributes, although slightly lower scores were observed for aroma and texture with sensory value of 7.5 and 7.2, respectively. Nonetheless, the overall acceptability of all samples remained high.

**Moisture loss in dried dates samples**

During drying operation, dates fruit samples was weighed at regular intervals to monitor the rate of moisture loss. The sample initially weighed 30 g and the weight measurements were taken every hour over a four-hour drying period. The samples dried

with the multifunctional thermal processing machine exhibited a progressive decline in weight, reducing the sample to 24 g after four hours, while the samples dried with the oscillatory dryer experienced a sharp decline in weight.

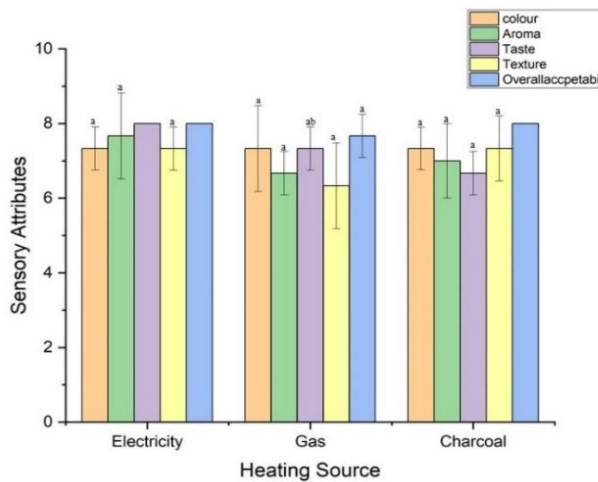


Figure 8: Effect of heating sources on sensory attributes of roasted plantain

This substantial difference in final weight can be attributed to the design and airflow efficiency of both dryers. The MTP machine which features an enclosed drying space and utilizes stainless steel bowls (non-perforated) limited air flow and retained moisture in the date fruits compared to the oscillatory dryer which features a ventilated mesh wire, which allows for better heat and mass transfer. This is similar to Norhadi *et al.* (2020), who reported that tray dryers achieved higher drying rates and better product quality than oven dryers, as oven dryer’s limited airflow led to less efficient moisture removal. The result of this evaluation is presented in Figure 9.

**Thermal efficiency**

The thermal efficiency of the multifunctional thermal processing machine was assessed for baking, roasting, and drying processes. Baking 2.4 kg of scones (useful heat = 726.64 kJ) showed efficiencies of 5.08% for electric baking ( $Q_{in} = 14.3$

MJ), 6.0% for gas baking ( $Q_{in} = 12.1$  MJ), and 1.15% for charcoal baking ( $Q_{in} = 63.2$  MJ).

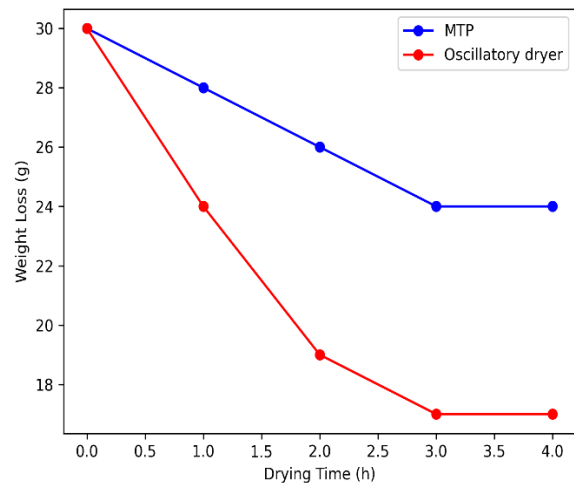


Figure 9: Effect of MTP machine and Oscillatory dryer on the weight loss in date during drying

Roasting 1.2 kg of plantain (useful heat = 469.8 kJ) yielded efficiencies of 2.09% for electric roasting ( $Q_{in} = 22.5$  MJ), 3.61% for gas roasting ( $Q_{in} = 13.0$  MJ), and 0.61% for charcoal roasting ( $Q_{in} = 77.0$  MJ). Gas-based processes consistently demonstrated the highest efficiencies, likely due to lower energy inputs, while charcoal-based methods were the least efficient. For drying 2 kg of wet dates with electricity ( $Q_{in} = 67.28$  MJ), the useful heat was 840.2 kJ, resulting in a thermal efficiency of 1.25%, the lowest among the processes, primarily due to the high energy required for water evaporation. These findings suggest that gas heating optimizes energy use, offering insights for improving the machine’s design to enhance thermal efficiency.

**CONCLUSIONS**

This study successfully designed, fabricated, and evaluated a multifunctional thermal processing machine capable of roasting, baking, and drying, utilizing electricity, gas, and charcoal as energy sources. Gas proved to be the most efficient, reaching the target temperature of 200 °C within 25 mins while consuming 5.04 - 13 MJ of energy in the

processing operations and achieving the highest chamber temperature of 298°C, making it particularly suitable for high-temperature applications. Electricity, while slower, provided superior temperature stability and precise controllability, with energy consumption ranging between 16.82 – 22.5MJ primarily attributed to the heating element. In contrast, charcoal was the least effective, requiring 42.14 - 77.0 MJ of energy to perform the desired thermal processing operations. During drying operation, the machine reduced the moisture content of date fruit from 29% to 17.24% within four hours at 70°C using electricity, with consistent weight reduction from 30 g to 24 g, confirming effective drying performance. Electrical heating baked scones in the shortest time, followed by gas and charcoal. Charcoal excelled in sensory quality, while electricity ensured efficiency. Gas roasted plantains fastest, followed by electricity and charcoal. Electricity yielded the best taste and texture while gas ensured uniformity. The machine's compatibility with multiple energy sources and user-friendly controls makes it a reliable, scalable solution for small- to medium-scale food processing enterprises, particularly in regions with unreliable electricity.

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