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Design and Development of an Earthen Oven with Automatic Temperature Control

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Abstract

The traditional earthen oven has been a staple in many cultures for drying and baking, but it lacks the ability to control and maintain a consistent temperature. This limitation can lead to uneven drying results and longer drying times, which may not meet the demands of modern drying needs. The incorporation of an automatic temperature controller to the earthen oven aimed to address this problem. The materials employed in fabricating the oven included clay, mild steel rods, mild steel angle bars, insulation fibre and so on. Other accessories were temperature controller, AC-DC inverter, 12V Battery which were acquired from the open market. The insulation layer of the oven comprised a mixture of clay and metallic straw. The methodology included testing the oven with varying air flow rates ranging from 2 to 4 m/s, heating times ranging from 10 to 30 minutes, and charcoal masses ranging from 5 to 25 kg. Linear shrinkage value of -8.9 indicated uniform heating of the oven walls, leading to effective retention of heat within the oven drying chamber. The grain size distribution, with percentages passing ranging from 93.44 to 100%, indicating finer particles that would result in cohesive and impermeable material with high strength, permeability, and thermal conductivity of the oven walls. The plastic index of 18.7% indicated a wider range of moisture content for workability to prevent cracking or collapsing during use, Liquid Limit (LL) of 44.5%. LL of 44.5% indicated significant improvement against cracking and crumbling of the oven clay walls. The range of temperature obtained from evaluation of the earthen oven was in the range of 280-300°C. As the heating time increased for a fixed air flow rate of 2, 3 and 4 m/s, it was seen that longer duration of running the oven tended to result in a steadier retention of the high temperature. Higher oven temperature was observed as a function of air flow rate which acted as a catalyst to the burning charcoal. The findings provide a promising solution to inconsistent drying outcomes in traditional earthen ovens. The design and operating parameters should be optimized for different drying applications.

Keywords: Earthen oven, Automatic temperature controller, Temperature control, Drying outcomes.

1 | Introduction

Earthen ovens have been used for centuries as a traditional method of drying in various cultures around the world [1]. These ovens are typically made from clay, sand, and other natural materials, and are known for their ability to retain heat and cook food evenly. In recent years, there has been a growing interest in incorporating modern technology into these traditional ovens to improve their efficiency and convenience.

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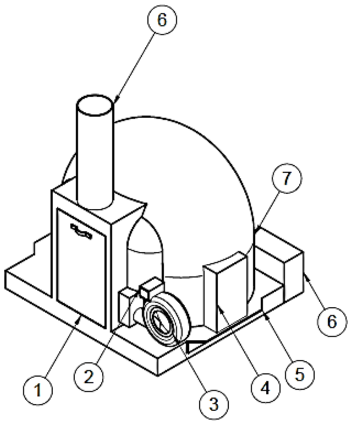
One such innovation is the development of earthen ovens with automatic temperature control. The idea of designing and producing an earthen oven with automatic temperature control was inspired by the need for a more efficient and reliable drying appliance in rural and off-grid areas [2]. Traditional earthen ovens are known for their ability to retain heat, but they can be difficult to control and maintain a consistent temperature. By adding automatic temperature control to the design, is to improve the performance and efficiency of these ovens, making them more suitable for modern drying needs [3]. An earthen oven with automatic temperature control is designed to regulate the heat inside the oven without the need for constant monitoring and adjustment by the end user. This is achieved through the use of sensors and a control system that automatically adjusts the airflow and fuel supply to maintain a consistent temperature throughout the drying process. Drying is one of the oldest methods of preserving food. Primitive societies practiced the drying of meat and fish in the sun long before recorded history [4]. Today the drying of food is still important as a method of preservation. Dried foods can be stored for long periods without deterioration occurring. This feature allows for more precise control over the drying process, resulting in better-tasting and more evenly cooked food. This not only makes drying with an earthen oven more convenient, but also ensures more consistent and reliable results. The oven is typically made from a mixture of clay, sand, and other natural materials, which are shaped into a dome or barrel shape. The oven is then heated using a wood fire, and the temperature is controlled using a thermostat and other mechanism. The design and production of an earthen oven with automatic temperature control typically involves incorporating electronic components such as temperature sensors, a control unit, and a fan or blower for regulating airflow [5]. These components are integrated into the traditional earthen oven structure, allowing for seamless operation without compromising the authenticity of the drying experience. The uses of an earthen oven with automatic temperature control are diverse and versatile. From baking bread and pizza to roasting meats and vegetables, this innovative appliance can handle a wide range of drying tasks with precision and efficiency. Whether used in a professional kitchen or a backyard setting, this technology-enhanced earthen oven offers a unique and sustainable cook drying solution that combines tradition with modern convenience. The development of earthen ovens with automatic temperature control which is the primary focus of this study represents a significant advancement in the field of traditional drying methods [6]. By combining the time-tested principles of earthen oven construction with modern technology, these innovative appliances offer a practical and efficient solution for drying enthusiasts and professionals alike. With their ability to maintain consistent temperatures and produce the required results, these ovens are sure to become a staple in kitchens around the world. Over the years, a number of studies have been conducted on the design of an earthen oven. An investigation was conducted by [7] on the drying characteristics of blueberries using Hot Air Convective Drying (HACD), Microwave Vacuum Drying (MWVD) and their combination (HACD+MWVD) on the drying kinetics, colour, total polyphenols, anthocyanins antioxidant capacity and texture of frozen/thawed blueberries. Drying resulted in reduction of total polyphenols content and antioxidant capacity (69% and 77%, respectively). The highest content of total polyphenols was noted after HACD at 90 °C. Drying processes caused a significant decrease (from 70% to 95%) in the content of anthocyanins. The highest content of anthocyanins and the strongest antioxidant capacity was found in blueberries dried using HACD at 90 °C+MWVD. Among drying methods, HACD at 90 °C + MWVD satisfied significant requirements for dried fruits i.e. short drying time and improved product quality. The effect of several parameters was studied by [8] on what would become of the drying performance of a pulsed fluidized vibrated bed made of biomass particles. The effects of gas flow rate, bed temperature, pulsation frequency and vibration intensity on drying performance were systematically investigated. While higher temperature and gas flow rate are favoured in drying, there exists an optimal range of pulsation frequency between 0.75 Hz and 1.5 Hz where gas-solid contact is enhanced in both the constant rate drying and falling rate drying periods. The recommendation made at the end of the study suggested that high temperature and high gas flow rate will allow for an effective drying. Drying characteristics of ginger rhizome using five different drying processes which included hot air drying method, Freeze Drying (FD) method, Infrared (IR) drying method, microwave drying method, the intermittent microwave, and the convective drying method was studied by [9]. In his study, quality attributes of the dried samples were compared in terms of volatile compounds, 6, 8, 10-gingerols, 6-shogaol, antioxidant activities and microstructure. Results showed that Air-Drying AD and IR drying were good drying methods to preserve volatiles. FD, IR and Intermittent Microwave & Convective Drying (IM&CD) led to higher retention of gingerols, TPC, TFC and better antioxidant activities. However, FD and IR had relative high energy consumption and drying time. The outcome also showed that microwave drying and the convective drying method gave positive results when considering the preservation of thermo-sensitive materials, and the advantage of low power consumption. Then, [10] in their work paid attention to the analysis of the mechanism of vibration-energy-transfer using wave propagation in drying. The pressure wave was produced from a vibrating base at the bed bottom and transferred to the particle bed via an air gap formed between the distributor and particle bed. The wave propagation process and its mechanism in a fluidized bed was analyzed. The pressure-wave propagation parameters were numerically calculated from the detected wave signals. The wave propagation velocities were found to be in the range of 9–75 m/s in the experiments. This study had in it the utilization of sensors to better detect the wave signals and to with it estimate the pressure-wave propagation parameters associated with the drying process. In what appeared to be an advancement in the application of technology to drying. [11], came up with a prototype of an automated device in the form of a cocoa drying house. In the drying house an automated roof was installed in order for it to be automatically controlled (opened and closed) depending on the appearance of sunlight. It also had an automatic heaters, an automated fermenter and a remote control feature for the automated components heaters which could also be remotely controlled. Traditional earthen ovens lack the ability to control and maintain a consistent temperature, leading to uneven drying and potential food safety concerns. One of the primary problems necessitating the development of an earthen oven with automatic temperature control is the inconsistency in drying results. Traditional earthen ovens rely on manual monitoring and adjustment of the fire to regulate temperature, which can be challenging for inexperienced users. In Uyo, Akwa Ibom State of Nigeria, the use of earthen-ovens in carrying out the quotidian baking activities has recorded certain deficiencies due to the inability to detect and regulate the operating temperatures at a given time. This has given rise to such ovens running at high temperatures leading to the destruction of the items that are undergoing the drying process. This is due to the absence of measurement devices to monitor the variation in temperatures at different times for easy regulation. This often results in food being undercooked or burnt, leading to wasted ingredients and unsatisfactory outcomes. Furthermore, the lack of temperature control in traditional earthen ovens poses a risk to food safety. Inadequate drying temperatures can result in the growth of harmful bacteria, putting consumers at risk of foodborne illnesses. This study is focus on the design and production of an earthen oven embedded with an automatic temperature control in the oven and performance evaluation of the produced earthen oven to evaluate the influence of processing parameters in the temperature of the oven.

2 | Design of the Oven

The clay-oven was first conceptualized with sketches and then designed using AutoCAD. *Fig. 1* shows the pictorial model of the clay oven.



8	CHIMNEY	MILD STEEL
7	OVEN BODY	CLAY
6	12V BATTERY	BOUGHT OUT
5	OVEN HANDLE	MILD STEEL
4	AC-DC INVERTER	BOUGHT OUT
3	BLOWER	BOUGHT OUT
2	TEMPERATURE CONTROL	BOUGHT OUT
1	INSULATED OVEN DOOR	MILD STEEL
S/N	**ITEM**	**DESCRIPTION**
	PARTS LIST	

Fig. 1. CAD model of the automated clay oven.

The oven consists of eight main components, which aid in its optimal functionality. The components which are discussed as follows include oven door, temperature controller, blower, AC-DC Inverter, oven handle, 12V Battery, oven body and chimney. One of the initial steps in designing the earthen oven with an automatic temperature controller was to determine the size and shape of the oven. The size of the oven depended on the intended use and the amount of food that needs to be dried. It was important to consider these factors carefully to ensure that the oven meets the desired requirements. Once the size and shape of the oven have been determined, the next step was to select the materials for construction. The earthen oven was made from clay, sand, and metallic straw. The materials were chosen to withstand high temperatures and provide good insulation to ensure even drying. After selecting the materials, the next step is to produce the oven structure. Based on design, the values of L, W and H were 284 mm, 210 mm and 130 mm respectively. Substituting these values into *Eq. (1)*, we have

$$V_{ovc} = L \times W \times H, \quad (1)$$

where L was the length, W was the width and H was the height of the compartment.

$$V_{ovc} = 284 \times 210 \times 130,$$
$$V_{ovc} = 775320 \text{ mm}^3 \ (0.77532 \text{ m}^3).$$

Similarly, *Eq. (2)* was used to determine the surface area of the drying compartment.

$$A_{oven} = 2 \times (L \times W + L \times H + W \times H),$$

$$A_{oven} = 2 \times (284 \times 210 + 284 \times 130 + 210 \times 130), \quad (2)$$

$$A_{oven} = 2.477200\text{mm}^2 \ (2.4772 \text{ m}^2).$$

The mass of oxygen required for the combustion of a given mass of charcoal, $m_{charcoal}$ was computed and converted to the volume of air needed. Assuming the stoichiometric combustion of charcoal as follows:

$$C + O_2 \rightarrow CO_2. \quad (3)$$

This implies that for every mole of carbon, one mole of oxygen is required for complete combustion. The stoichiometric molar mass of oxygen is 32 g/mol. The moles of oxygen required for the combustion of $m_{charcoal}$ of charcoal is given by *Eq. (4)*.

$$\text{moles of oxygen} = \frac{\text{moles of carbon}}{\text{stoichiometric coefficient of carbon}} \times \text{stoichiometric coefficient of oxygen}. \quad (4)$$

The number of moles of carbon required can be calculated using the molar mass of carbon as shown in *Eq. (5)*.

$$\text{moles of carbon} = \frac{m_{charcoal}}{\text{molar mass of carbon}}. \quad (5)$$

Then, the moles of oxygen required was determined using *Eq. (6)*.

$$\text{Moles of oxygen} = \frac{\text{moles of carbon}}{1} \times 1 = \text{moles of carbon}. \quad (6)$$

Converting moles of oxygen to mass of oxygen m_{O_2}

$$m_{O_2} = \text{moles of oxygen} \times \text{molar mass of oxygen}. \quad (7)$$

Therefore, the volume of air required is given by *Eq. (8)*.

$$Q_{air} = \frac{m_{O_2}}{\text{density of oxygen}} \times \frac{1}{0.21}. \quad (8)$$

3 | Production of the Earthen Oven

After the choice of clay was made, it was soaked in a bucket of water to soften it, the mixture was thoroughly sieved to get rid of impurities and other unwanted substances. This was adequately achieved after soaking it for 3-4 days. The processed clay was poured into a bag and pressed for the water to be separated from the clay, thereafter, it was spread out for proper drying on a clean and a sand-free surface. Then, a measured quantity of already fired clay was grounded and properly mixed into the clay, this was to done to boost the mechanical properties of the clay so as to avoid cracks and impending failure. Wooden moulds with dimensions 5cm x 5cm x 10cm was formed to enhance the compression of the clay into shapes, same sizes and weight as desired for moulding the oven. These formed bricks helped in increasing the strength, durability, the ability of the oven to withstand heat at the temperature desired for baking. After the framing, the prepared moulds were used to line the oven walls. The clay was subsequently mixed with some quantity of water and the paste formed was placed in the moulds that were prepared and rammed to compact it. Additional clay paste was added as required. Thereafter, the moulded clay was allowed to cure for two weeks using open-sun drying. The bricks were then removed from the moulds and placed in the framework that was produced, then clay paste was used to bind the bricks together. More clay was applied to the walls of the oven, then allowed to sun-dry for twenty-eight days. After drying, the oven door was installed. It was produced using mild steel sheets and a fiberglass insulation wool was placed inside the steel door and welded up. Subsequently, it was fixed to the oven using a pair of hinges. Thereafter, the blower was installed as well as the temperature controller, the thermocouple and associated power supply components which were purchased. The automatic temperature controller regulated the temperature inside the oven, ensuring that it stays at the desired level for drying. The temperature controller can be programmed to maintain a specific temperature or to follow a preset drying schedule. This feature is essential for consistent and precise drying outcome. The access door of the oven was made with a double-walled mild steel plate with fiberglass wool as the insulation material. The heat transfer calculation was carried out using the Fourier's law for heat conduction as given in *Eq. (9)*. The thermal conductivity of clay used was 1.17W/(m.K) after its moisture content was determined [12].

$$Q = \frac{kA\Delta T}{d}, \quad (9)$$

where Q is the rate of heat transfer, K is the thermal conductivity, A is the surface area, ΔT is the temperature difference, and d is the thickness of the material.

$K = 1.17W/(m.K)$, $A = (2.4772\ m^2)$, $\Delta T = 215^0$ and $d = 3mm$.

Inputting the parameters into *Eq. (9)* yields

$$Q = \frac{1.17 \times 2.4772 \times 215}{3},$$

$$Q = 207.71\ W/M^2.$$

Also, the overall heat transfer coefficient, U through the oven door was calculated using *Eq. (10)*.

$$U = \frac{1}{\frac{1}{U_{ms}} + \frac{t_{fwl}}{k_{fwl}}}, \tag{10}$$

where U_{ms} the heat transfer coefficient of mild steel plate is, t_{fwl} is the thickness of the fiberglass wool and k_{fwl} is the thermal conductivity of fiberglass wool. Prior to the moulding of is the oven body, the design consideration for the oven was critical on the choice of the refractory material. In order to determine the plasticity of the clay to be used, the sample had to undergo some laboratory experiments to ensure its usability for the desired purpose. *Fig. 2* shows the skeletal framework of the Oven. After applying all the methods outlined, the earthen oven was produced as shown in *Fig. 3*.

Fig. 2. Skeletal framework of the oven.

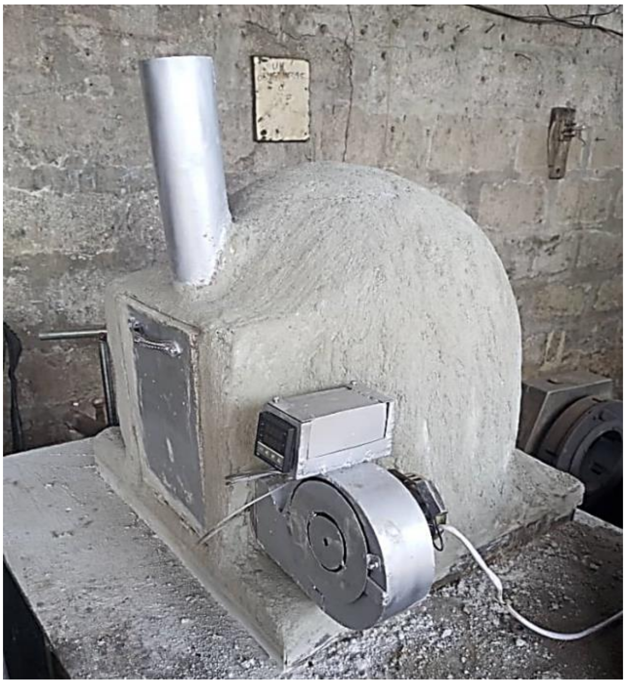


Fig. 3. Produced earthen oven.

The laboratory analyses were performed according to British standard methods of test for soil for civil engineering purposes (BS 1377: Part 1-9, 1990). The laboratory test was carried out to investigate the basic geotechnical properties of the clay. The test was focused on determining the particle/size distribution, natural moisture content, atterberg limit Liquid Limit (LL), plastic limit (PL) and Plasticity Index (PI) Linear shrinkage test, compaction.

$$\text{Mass of moisture} = \text{Mass of wet sample+ can- Mass of dry sample} + \text{can}, \quad (11)$$

$$\text{Mass of dry sample} = \text{Mass of dry sample} + \text{can - Mass of empty can} \quad (12)$$

$$\text{Moisture content (\%)} = \text{Mass of moisture/ Mass of dry sample} * 100 \quad (13)$$

$$\text{Actual weight} = \text{Total weight} - \text{Weight retained} \quad (14)$$

$$\text{Percentage retained} = \frac{\text{Weight Retained}}{\text{Total Weight}} \times 100 \quad (15)$$

$$\text{Percentage passing} = 100 \text{ - Percentage retained} \quad (16)$$

$$\text{Weight of dry soil} = (\text{weight of dry soil} + \text{tin}) - \text{weight of tin} \quad (17)$$

$$\text{Weight of water} = (\text{weight of wet soil} + \text{tin}) - (\text{weight of soil} + \text{tin}) \quad (18)$$

$$\text{Moisture content (\%)} = \frac{\text{Weight of Water}}{\text{Weight of dry Soil}} \times 100 \quad (19)$$

$$\text{Plasticity index} = \text{LL} - \text{PL}. \quad (20)$$

$$\text{Linear shrinkage LS, } (100\% * {}^{(1-L_D)}/_{L_O}). \quad (21)$$

4 | Results of Laboratory Tests

Different data sets were obtained prior to the production of the earthen oven. *Table 1* shows the result of the sieve analysis obtained from the laboratory experiment conducted on the clay while *Fig. 4* shows the Grain size distribution curve. Also, *Table 2* shows the Consistency test result while *Fig. 5* presents the Result of LL test, and *Table 3* is the result obtained during the linear shrinkage limit test.

Table 1. Sieve analysis.

Weight of dry sample	500.0	g	Date	12/10/2023
Weight of washed sample	48.0	g	Air Dry M_c	0.31%
Washed thro: Sieve 200	452.0	g		
Absolute mass	498.6	g	Sample	CLAY
Sieve Aperture (mm)	**Weight Retained (g)**	**% Retained**	**Cum % Retained**	**% Passing**
4.750	0.00	0.00	0.00	100.00
3.350	0.80	0.16	0.16	99.84
2.360	0.70	0.14	0.30	99.70
1.180	1.60	0.32	0.62	99.38
0.850	2.80	0.56	1.18	98.82
0.600	3.00	0.60	1.79	98.21
0.400	0.90	0.18	1.97	98.03
0.250	1.60	0.32	2.29	97.71
0.150	13.20	2.65	4.94	95.06
0.075	8.10	1.63	6.56	93.44
PAN	0.9	0.18		

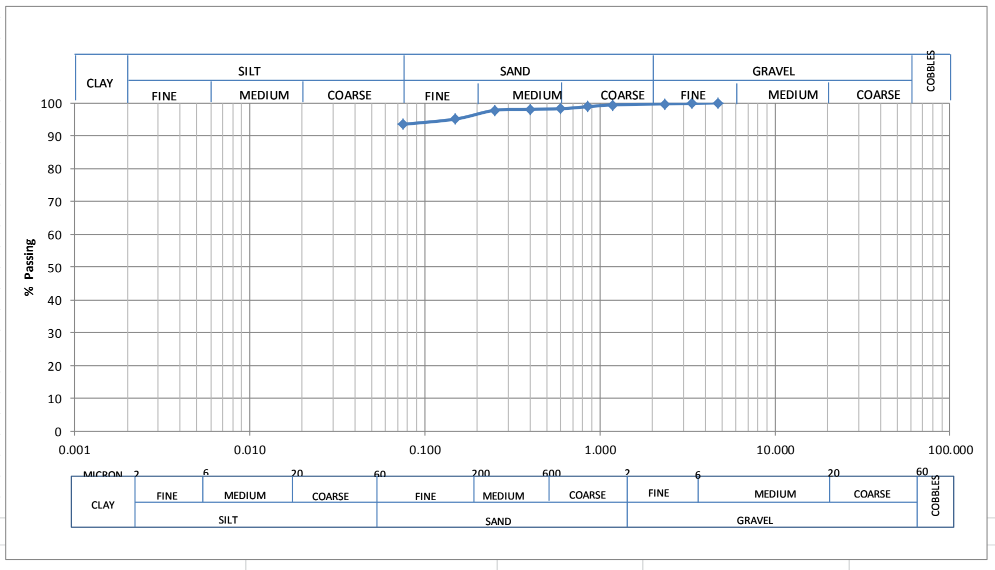


Fig. 4. Grain size distribution curve.

Table 2. Consistency test.

Consistency Test										
Location	**Ikot Ebom Itam**									
Date of Test	14/10/2023			Sample					Laterite	
	LL								PL	
Number of blows	17		27		39		54			
Container no.	MA	AQ	EGA	CV2	IA	SPI	UP	NST	C2C	CI
Mass of container, g	17.60	21.50	18.80	18.20	21.90	18.20	17.60	17.60	21.70	18.00
Mass of wet soil + container, g	37.80	45.40	38.80	41.90	44.00	42.80	38.70	41.50	37.20	35.20
Mass of dry soil + container, g	31.60	37.90	32.40	34.60	37.30	35.30	32.40	34.30	33.90	31.80
Mass of moisture, g	6.20	7.50	6.40	7.30	6.70	7.50	6.30	7.20	3.30	3.40
Mass of dry soil, g	14.00	16.40	14.40	16.40	15.40	17.10	14.80	16.70	12.20	13.80
Moisture content (%)	44.29	45.73	44.44	44.51	43.51	43.86	42.57	43.11	27.05	24.64
Moisture content (%)	45.01		44.48		43.68		42.84		25.84	

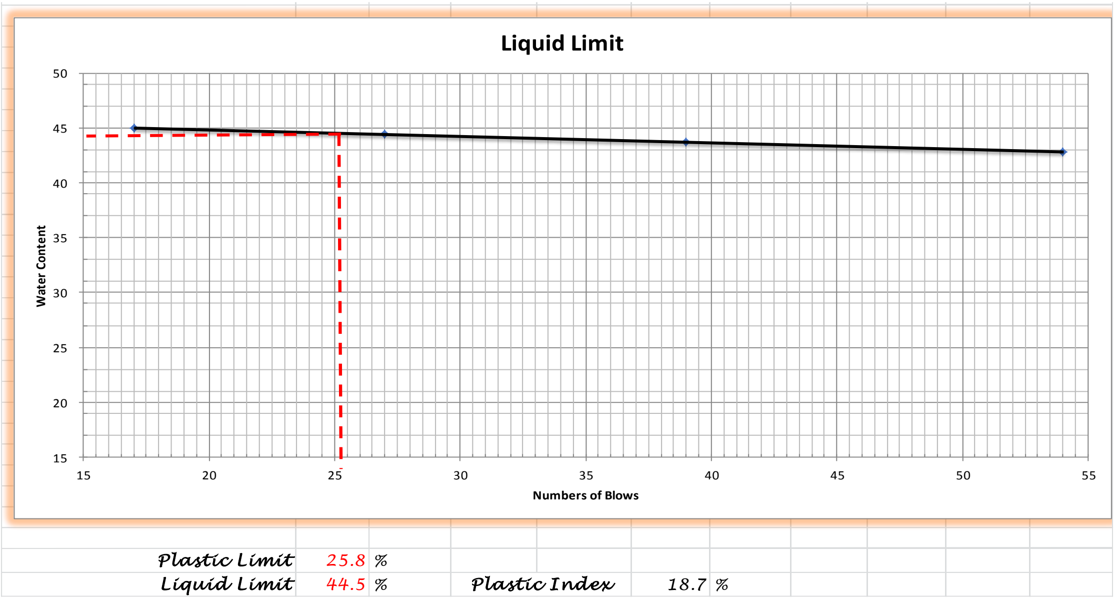


Fig. 5. Result of liquid limit test.

Table 3. Result of linear shrinkage limit test.

		Date	14 - 10 - 2023
Specimen Reference			
Location			
Initial length	Lo	mm	140
Oven dried length	LD	mm	127.6
Linear shrinkage LS = 100(1-LD/ Lo)			-8.9

$$\frac{127.6}{140} = \text{-}0.0885714286,$$
$$LS = 100(\text{-}0.0885714286),$$
$$LS = \text{-}8.85714286.$$

The clay PL, LL, plastic index, and grain size distribution are important parameters that influence the behaviour of clayey soils in various engineering applications. In the context of an earthen oven, these properties play a crucial role in determining the structural integrity and thermal performance of the oven.

The PL of 25.8% as shown in *Fig. 5* indicates the moisture content at which the clay soil transitions from a plastic to a semi-solid state. This property is significant in the construction of the oven walls, as it determines the workability and moldability of the clay mixture. A higher PL would result in a more malleable material that can be easily shaped and moulded into the desired form. On the other hand, a lower PL may lead to cracking and deformation of the oven structure during drying and firing. In this case, clay with PL of of 25.8% is ideal for constructing an earthen oven, as it provides good balance of workability and strength. In other words, the clay will become plastic when its moisture content reaches 25.8% of its dry weight.

The LL of 44.5% represents the moisture content at which the clayey soil begins to flow under its own weight. This property is crucial in determining the water content required for proper compaction and bonding of the clay mixture. A higher LL would result in a more fluid material that can be easily spread and compacted, while a lower LL may require additional water for proper mixing and compaction. In this case, LL of 44.5% as shown in *Fig. 5* indicates that the clay has a high moisture content which can have positive impact on the cracking and crumbling of the of the oven clay walls.

The plastic index of 18.7% is the difference between the LL and PL, indicating the range of moisture content over which the clayey soil exhibits plastic behaviour. This property is important in controlling the shrinkage and cracking of the oven walls during drying and firing. A higher plastic index would result in a wider range of moisture content for workability, while a lower plastic index may require more precise control of moisture content during construction. This value (18.7% plastic index as shown in *Fig. 5*) is quite ideal, indicating that the clay has a moderate level of plasticity, which can be beneficial for the oven. This is because clay with this value is structurally sound, and likely to have good binding properties which can help hold the oven together and prevent it from cracking or collapsing during use.

The grain size distribution, with percentages passing ranging from 93.44 to 100% 9 (see *Table 1* and *Fig. 4*), indicates the proportion of different particle sizes in the clayey soil. This property influences the strength, permeability, and thermal conductivity of the oven walls. A higher percentage of finer particles would result in a more cohesive and impermeable of the clay oven, while a higher percentage of coarser particles may lead to reduced strength and increased porosity. In this case, the range (93.44 to 100%) of percentage of clay passing through the sieve aperture would result in increased strength and thermal resistance of the earthen oven. The results also showed that 0.00 to 2.65% of the particles remained in the 0.075 to 4.750mm sieve aperture. This indicates that the clay sample had a relatively uniform distribution of particle sizes within this range that signifies high strength of the clay oven walls. This information is valuable for understanding the behaviour of the clay under different loading conditions and for designing appropriate engineering structures.

The linear shrinkage of clay in earthen ovens is a critical factor to consider when constructing and using earthen oven. A linear shrinkage value of -8.9 indicates that the clay used in the oven will not undergo a significant amount of contraction as it dries and is fired. This has important implications on the structural integrity and performance of the oven. One of the key implications of a linear shrinkage value of -8.9 is that the walls of the earthen oven has very minimal potential for cracking and less tendency for structural failure of the oven. As the clay shrinks during the drying and firing process, limited amount of internal stress build up within the material occurs. However, if these stresses exceed the strength of the clay, cracks can form, compromising the integrity of the oven. This can lead to heat loss during drying, uneven heating of food, and ultimately, a decrease in the efficiency and effectiveness of the oven. Furthermore, the linear shrinkage of clay in earthen ovens can also impact the overall drying experience positively. A lower shrinkage value like -8.9 can result in uniform heating of the oven walls, leading to effective heating within the drying chamber. This can make it easier to achieve consistent and predictable drying results, improving the quality of the food being prepared.

5 | Results of the Oven Test-Run

Fig. 6 shows the mass of charcoal plotted against the final temperatures using a fixed airflow rate of 2 m/s and the three variations of heating time.

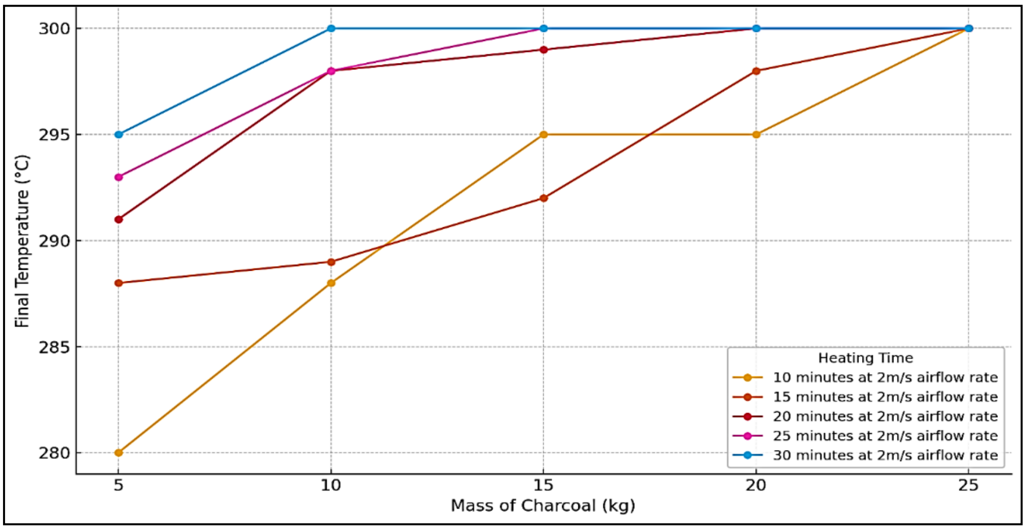


Fig. 6. Plot of temperature and mass of charcoal for 10-30 minute operation at 2m/s airflow rate.

Fig. 7 shows the mass of charcoal plotted against the final temperatures using a fixed airflow rate of 3 m/s and various three variations of heating time

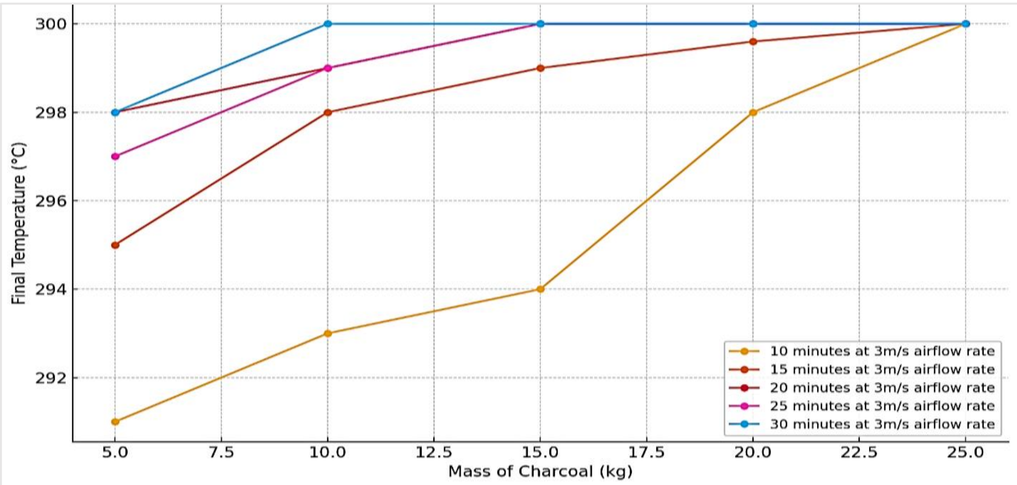


Fig. 7. Mass of charcoal plotted against temperature for 10-30 minute operation at 3m/s airflow rate.

Fig. 8 show the mass of charcoal plotted against the final temperatures using a fixed airflow rate of 4 m/s and various three variations of heating time

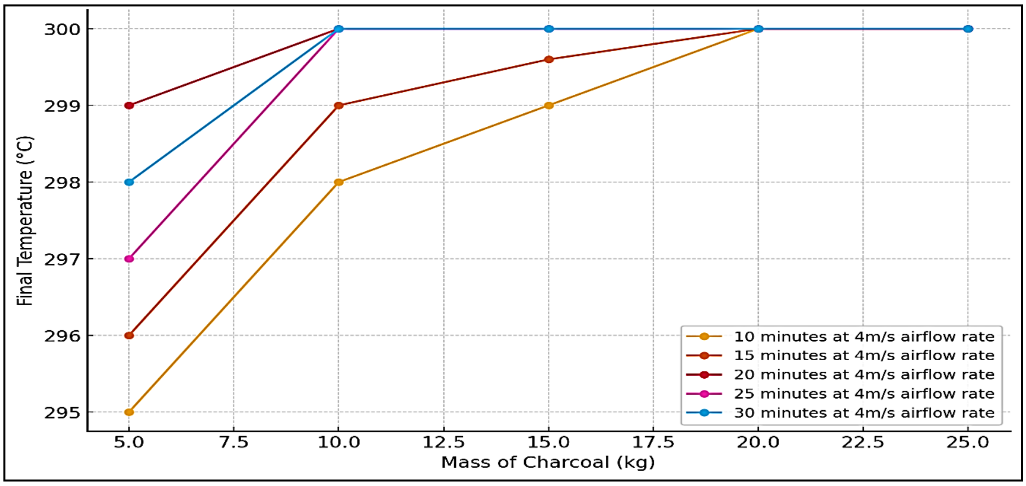


Fig. 8. Mass of charcoal plotted against temperature for 10, - 30 minute operation at 4m/s airflow rate.

6 | Effects of Charcoal Mass on Temperature

Charcoal is a common fuel source for these ovens due to its high heat output and long burning time. When a larger mass of charcoal is used in the oven, it will produce more heat and reach higher temperatures than if a smaller amount of charcoal is used. This is because the additional fuel provides more energy to the oven, allowing it to heat up more quickly and maintain a higher temperature throughout the drying process. The clay oven test-run shows that the mass of charcoal available for burning has a direct effect on the final temperature of the oven. This is evident in the range of values obtained when the oven was test-run at fixed intervals with increasing masses. The relationship between the mass of charcoal being burned and the final temperature of the oven are presented in *Fig. 6 - 8*. *Fig. 6*, shows the operation of the oven at 2m/s airflow rate for 10 minutes and took about 20-25Kg of charcoal to attain the temperature range of 295-300 °C. Furthermore, 15 minutes operation time took the same 20-25Kg of charcoal to attain a higher temperature range of 298-300 °C. For 20 minutes of the oven operational time, 300°C oven temperature was achieved at 20-25kg of charcoal. Additionally, operating the oven for 2m/s airflow rate for 25 minutes took about 15-20Kg of charcoal to attain the temperature range of 295-300°C. However, for 30 minutes of the oven operational time, 300°C oven temperature was achieved at 10-15Kg of charcoal. This implies that higher oven temperature is fast achievable at higher operational time and less mass of charcoal due to wide area of heat distribution and retention.

As shown in *Fig. 7*, operating the oven for 3m/s airflow rate for 10, 15, 20, 25 and 30 minutes took about 10-25Kg of charcoal to attain temperature ranges of 294-300, 298-300°C, 297-300°C, 298-300°C and 300. Again, this indicated that higher oven temperature is a function of air flow rate and heat transfer.

Finally as shown in *Fig. 8*, operating the oven for 4m/s airflow rate for 10 and 15 minutes took about 20Kg of charcoal to attain the peak temperature of 300°C. However, the same airflow rate and 20, 25 and 30 minutes of operation took lesser mass of charcoal of 10 Kg to attain the peak oven temperature of 300°C. As mentioned before, this is due to the higher airflow rate which acts as a catalyst to the burning charcoal. The results demonstrate that the mass of charcoal used significantly influences the final temperature of the clay oven. As shown in *Figs. 6-8*, increasing the charcoal mass resulted in higher oven temperatures across all operational conditions. For instance, at an airflow rate of 2 m/s and a heating time of 10 minutes *Fig. 6* a temperature range of 295–300°C was achieved with 20–25 kg of charcoal. Similarly, at higher airflow rates of 3 m/s and 4 m/s, the relationship between charcoal mass and temperature remained consistent. These findings align with the principle that increased fuel mass provides more energy for combustion, resulting in higher thermal output. However, diminishing returns were observed at maximum temperatures (300°C), beyond which increasing the charcoal mass had no further effect. This suggests that the oven reached its thermal limit, influenced by factors such as insulation and heat loss mechanisms. This observation correlates with the findings of [13] that the true density of charcoal prepared under compression of 0.5 MPa and at a heating rate of 2 °C/min increased with pyrolysis temperature, especially at temperatures higher than 450°C and also noted that excessive charcoal mass does not always translate to proportional temperature increase due to heat saturation.

7 | Effects of Airflow Rate on Temperature

The rate of air flow in an earthen oven can have a significant impact on the temperature inside the oven. When air flow is restricted, heat is trapped inside the oven, leading to higher temperatures. On the other hand, when air flow is increased, heat is allowed to escape more easily, resulting in lower temperatures. This relationship between air flow rate and temperature is crucial for achieving consistent and reliable drying results in an earthen oven. One of the main reasons why controlling air flow is important in an earthen oven is because it affects the distribution of heat. When air flow is restricted, heat tends to accumulate in certain areas of the oven, leading to uneven drying. As the heating time increased for a fixed air flow rate of 2, 3 and 4 m/s, it was seen that longer duration of running the oven tended to result in a steadier retention of the high temperature. This result agrees with the study carried out by [14]. Their analysis also showed the temperature profile to be rising and becoming steadier with increasing heating time. The effect of airflow on temperature stability was observed when the data obtained were compared. This indicated that airflow has a positive impact on the rate of heat being generated in an oven. With the airflow varying between 2 m/s and 4 m/s, temperatures in the ranges of 200˚C to 300˚C were obtained. The temperature controller effectively prevented further increase by adjusting the airflow accordingly. The temperature inside the oven is crucial for drying food properly, and one factor that can affect the temperature is the airflow rate through the charcoal bed. The airflow rate through the charcoal bed plays a significant role in determining the operation temperature of an earthen oven. When there is a high airflow rate, more oxygen is supplied to the charcoal, resulting in a higher combustion rate and therefore a higher temperature inside the oven [15]. This increased airflow rate results in a more efficient combustion process, leading to higher operation temperatures within the oven. On the other hand, a low airflow rate restricts the supply of oxygen, leading to a lower combustion rate and a lower temperature. One study found that increasing the airflow rate by adjusting the ventilation system resulted in a significant increase in the temperature inside the oven [16]. This demonstrates the direct impact of airflow rate on the operation temperature of the oven. Furthermore, the airflow rate through the charcoal bed can also affect the drying time and quality of the food. A higher temperature achieved through increased airflow rate can result in faster drying times, while a lower temperature may lead to undercooked food [17]. Additionally, the airflow rate can influence the flavour and texture of the food, as different temperatures can produce different drying outcomes. Controlling the airflow rate through the charcoal bed allows for better temperature regulation within the oven. By adjusting the airflow rate, the cook can maintain a consistent temperature throughout the drying process. This is crucial for ensuring that the food is cooked evenly and thoroughly, without any hot spots or uneven drying [18]. Airflow rate was shown to be a critical factor affecting the combustion process and, consequently, the final temperature of the oven. At a lower airflow rate of 2 m/s, higher masses of charcoal (20–25 kg) were required to achieve temperatures within the range of 295–300°C (*Fig. 6*). As the airflow rate increased to 3 m/s *Fig. 7,* the same temperature ranges were achieved with less charcoal (15–25 kg), indicating enhanced combustion efficiency. At the highest airflow rate of 4 m/s (*Fig. 8*), the catalytic effect of airflow became more pronounced. For instance, operating the oven for 20 minutes at this airflow rate required only 10 kg of charcoal to achieve the peak temperature of 300°C. This can be attributed to the increased oxygen supply, which accelerates the combustion process, allowing for faster and more efficient heat generation. These observations aligns with the findings of [19], where combustion process in vertical air staging coke oven was studied, noting that optimal airflow rates improve heat transfer and combustion efficiency. However, it is worth noting that excessively high airflow rates can lead to increased heat loss, a phenomenon not observed in this study but reported by [20], who studied the effects of airflow on oven temperatures.

8 | Effect of Heating Time on Final Temperature

One important factor that can affect the temperature of an earthen oven is the heating time of the charcoal. This study has shown that the longer charcoal is heated before being placed in the oven, the higher the temperature of the oven will be. This is because charcoal needs time to reach its maximum heat output. By allowing the charcoal to heat for a longer period, more heat is generated, resulting in a higher oven temperature. Previous studies have shown that the heating time of charcoal can significantly impact the temperature of an oven. For example, a study by [21], found that increasing the heating time of charcoal resulted in increase in oven temperature. This suggests that longer heating times can lead to higher temperatures in an earthen oven. Heating time had a significant impact on the final temperature, as longer operational times allowed for better heat retention and more efficient energy utilization. For example, at an airflow rate of 2 m/s *Fig. 6*, operating the oven for 10 minutes required 20–25 kg of charcoal to reach 295–300°C. Extending the operational time to 30 minutes resulted in the same peak temperature of 300°C with no additional charcoal mass.

This trend was even more pronounced at higher airflow rates. At 4 m/s (*Fig. 7*), the same peak temperature of 300°C was achieved with just 10 kg of charcoal when the heating time was extended to 30 minutes. This underscores the role of longer heating durations in enhancing thermal efficiency by allowing heat to penetrate the oven walls, reducing losses, and maximizing heat retention. These findings align with the observations of [22], who reported that extended heating times improve temperature uniformity and reduce fuel consumption in biomass-fueled ovens. However, this study highlights the combined effect of airflow rate and heating time, which together significantly reduce the charcoal mass required to reach peak temperatures. Furthermore, the airflow rate through the charcoal bed also affects the overall energy efficiency of the earthen oven. By controlling the airflow rate, the cook can optimize the combustion process, ensuring that the charcoal is burned efficiently and effectively. This not only helps to reduce fuel consumption but also minimizes the environmental impact of using the oven. Physical inspection of the oven during the test-run indicated that the surface of the oven could be touched by hand without feeling an amount of heat that could burn the hand compared to the higher temperature being recorded inside the oven. This showed the viability of clay as an insulation material and is thus suitable for use in oven production.

9 | Conclusion

The findings from the comprehensive test-run and analysis of the automated oven underscored its operational dynamics and performance characteristics. The study affirmed the significant influence of varying parameters on the oven's temperature profile. Specifically, the direct impact of charcoal mass on final temperature, the correlation between prolonged heating duration and enhanced temperature stability, and the positive influence of airflow on heat generation were key observations. These insights contributed to a deeper understanding of the interplay between key variables in oven functionality. Notably, the utilization of clay as an insulating material demonstrated its effectiveness in maintaining safe exterior temperatures despite high internal heat, thereby affirming its suitability for oven construction. However, airflow variations from 2 m/s to 4 m/s resulted in temperature ranges spanning 200˚C to 300˚C. The effective regulation of temperature was facilitated by the adept functioning of the temperature controller, swiftly adjusting the airflow to prevent further escalation. Overall, the study's outcomes paved the way for advancements in oven design and optimization, emphasizing the importance of considering factors such as charcoal mass, heating duration, airflow regulation, and choice of insulation materials for the development of efficient and safe automated ovens. The insights gained from this research had practical implications and offered valuable directions for further advancements in automated oven technology.

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Data Availability

The data supporting the findings of this study were obtained from experimental analyses and computational simulations. Due to confidentiality concerns and proprietary restrictions, the complete dataset is not publicly available. However, summaries of the analyzed data can be provided upon request.

Conflicts of Interest

The authors declare that they have no competing financial or personal interests that could have influenced the research and findings presented in this paper.

References

[1] Saxena, A., Goel, V., & Karakilcik, M. (2018). Solar food processing and cooking methodologies. *Applications of solar energy*, 251–294. https://doi.org/10.1007/978-981-10-7206-2_13

[2] Ramirez-Laboreo, E., Sagues, C., & Llorente, S. (2016). Dynamic heat and mass transfer model of an electric oven for energy analysis. *Applied thermal engineering*, *93*, 683–691. https://doi.org/10.1016/j.applthermaleng.2015.10.040

[3] Tümay, M., & Ünver, H. M. (2021). Design and implementation of smart and automatic oven for food drying. *Measurement and control*, *54*(3–4), 396–407. https://doi.org/10.1177/00202940211000084

[4] Knorr, D., & Augustin, M. A. (2023). Preserving the food preservation legacy. *Critical reviews in food science and nutrition*, *63*(28), 9519–9538. https://doi.org/10.1080/10408398.2022.2065459

[5] Ezema, C. N., Onuoha, O., Nwogu, N., Agulanna, A. C., & Victor, U. U. (2016). Intelligent oven temperature regulator. *Original research article journal of basic and applied research international*, *18*(4), 2395–3446. https://www.academia.edu/download/58821847/INTELLIGENT_OVEN_TEMPERATURE_REGULATOR.pdf

[6] Dev, S. R. S., & Raghavan, V. G. S. (2012). Advancements in drying techniques for food, fiber, and fuel. *Drying technology*, *30*(11–12), 1147–1159. https://doi.org/10.1080/07373937.2012.692747

[7] Zielinska, M., & Michalska, A. (2016). Microwave-assisted drying of blueberry (Vaccinium corymbosum L.) fruits: Drying kinetics, polyphenols, anthocyanins, antioxidant capacity, colour and texture. *Food chemistry*, *212*, 671–680. DOI:https://doi.org/10.1016/j.foodchem.2016.06.003

[8] Jia, D., Cathary, O., Peng, J., Bi, X., Lim, C. J., Sokhansanj, S., … & Tsutsumi, A. (2015). Fluidization and drying of biomass particles in a vibrating fluidized bed with pulsed gas flow. *Fuel processing technology*, *138*, 471–482. https://doi.org/10.1016/j.fuproc.2015.06.023

[9] An KeJing, A. K., Zhao DanDan, Z. D., Wang ZhengFu, W. Z., Wu JiJun, W. J., Xu YuJuan, X. Y., & Xiao GengSheng, X. G. (2016). Comparison of different drying methods on Chinese ginger (Zingiber officinale Roscoe): changes in volatiles, chemical profile, antioxidant properties, and microstructure. *Food chemistry, (in press).*, *197*, 1292–1300. https://doi.org/10.1016/j.foodchem.2015.11.033

[10] Wang, T.-J., Jin, Y., Tsutsumi, A., Wang, Z., & Cui, Z. (2000). Energy transfer mechanism in a vibrating fluidized bed. *Chemical engineering journal*, *78*(2–3), 115–123. https://doi.org/10.1016/S1385-8947(00)00160-1

[11] Sangster, N., Lalla, T., Roberts, R., Meyers, K., & and Rampersad, K. (2015). An Automated Cocoa Drying House for Use in a Small Developing Country. *International journal of engineering inventions*, *4*(10), 23–30. http://www.ijeijournal.com/papers/Vol.4-Iss.10/E04102330.pdf

[12] Dafalla, M. A. and Samman, A. (2016). Soil and backfill material of environmental friendly thermal properties. international journal of GEOMATE, 10(4), 2083 – 2087. https://doi.org/10.21660/2016.22.5380.

[13] Somerville, M., & Jahanshahi, S. (2015). The effect of temperature and compression during pyrolysis on the density of charcoal made from Australian eucalypt wood. *Renewable energy*, *80*, 471–478. https://doi.org/10.1016/j.renene.2015.02.013

[14] Hatou, C., Tchuen, G., & Woafo, P. (2020). Modelling, simulation and optimization of solid fuel bread ovens commonly used in developing countries. *Elsevier, heliyon*, *7*(3), 1–7. https://doi.org/10.1016/j.heliyon.2021.e06585

[15] Mencarelli, A., Cavalli, R., Greco, R., & Grigolato, S. (2023). Comparison of technical and operational conditions of traditional and modern charcoal kilns: a case study in Italy. *Energies*, *16*(23), 7757. https://doi.org/10.3390/en16237757

[16] Verboven, P., Datta, A. K., Anh, N. T., Scheerlinck, N., & Nicola\i, B. M. (2003). Computation of airflow effects on heat and mass transfer in a microwave oven. *Journal of food engineering*, *59*(2–3), 181–190. https://doi.org/10.1016/S0260-8774(02)00456-9

[17] İlter, I., Altay, Ö., Köprüalan, Ö., Ertekin, F. K., & Jafari, S. M. (2023). An overview of high-temperature food processes. *High-temperature processing of food products*, 1-43. https://doi.org/10.1016/B978-0-12-818618-3.00002-1

[18] Bhattacharjee, S., Mohanty, P., Sahu, J. K., & Sahu, J. N. (2024). A critical review on drying of food materials: recent progress and key challenges. *International communications in heat and mass transfer*, *158*, 107863. https://doi.org/10.1016/j.icheatmasstransfer.2024.107863

[19] Hu, X., Zhang, J., Yu, Z., Liu, Z., Guo, J., & Xu, C. (2024). Numerical study of the combustion process in the vertical heating flue of air staging coke oven. *Processes*, *12*(10), 2294. https://doi.org/10.3390/pr12102294

[20] Shahapuzi, N. S., Taip, F. S., Ab Aziz, N., & Ahmedov, A. (2015). The effects of airflow on oven temperatures and cakes qualities. *Pertanika journal science technology*, *23*(2), 339–350. https://core.ac.uk/download/pdf/153808209.pdf

[21] Syred, C., Griffiths, A. J., Syred, N., Beedie, D., & James, D. (2006). A clean, efficient system for producing Charcoal, Heat and Power (CHaP). *Fuel*, *85*(10–11), 1566–1578. https://doi.org/10.1016/j.fuel.2005.10.026

[22] Olugbade, T. O., & Ojo, O. T. (2018). Development and performance evaluation of an improved electric baking oven. *Leonardo electronic journal of practices and technologies*, *33*, 189–206. https://www.academia.edu/download/78035405/189_206.pdf