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Experimental Study of Superheated Steam Roasting of Coffee-Guinea Pepper Blend Powered by a Biogas Furnace

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Abstract

Roasting is a crucial step in determining the quality of coffee, particularly for the coffee-Guinea pepper blend widely consumed in Senegal. Guinea pepper (botanical name *Aframomum melegueta*) belongs to the Zingiberaceae family and is a spice. However, coffee-Guinea pepper blends on the market often have defects in taste and aroma, mainly due to inefficient, energy-intensive and environmentally harmful conventional roasting techniques (wood, gas or hot air). This study proposes a sustainable, innovative approach that uses superheated steam generated from biogas produced by fermenting cow dung in a 4 m^3 geomembrane biodigester. This Open Access biogas is used to fuel a burner that superheats the steam used for roasting Arabica coffee (11.06% moisture content) and Guinea pepper (8.75% moisture content). The efficiency of the system was assessed through biomethane production, thermal performance, moisture loss, color changes and Fourier transform infrared spectroscopy (FTIR). Results showed that biomethane production reached 59.1% by the 13th day, which was sufficient to generate steam at 250˚C. The coffee reached this temperature in 450 seconds (compared to 600 seconds for hot air), with the moisture content reduced to 1.5%, achieving excellent thermal homogeneity (with a maximum deviation of 5˚C). The guinea pepper was roasted using the residual heat from the coffee beans, reducing its moisture content from 8.75% to 3.23% without the need for any additional energy input. FTIR analysis confirmed the preservation of more aromatic compounds (intact C-H, C=O and C-O bands) than was observed with traditional methods. This approach also significantly reduces energy consumption and CO_2 emissions and eliminates the impact of deforestation.

Keywords

Biodigester, Coffee, Guinea Pepper, Roasting, Superheated Steam

1. Introduction

Coffee is one of the most popular beverages worldwide. It is renowned for its bioactive compounds and unique flavor [1]. In Senegal, over 70% of the population consumes coffee flavored with Guinea pepper. The quality of coffee depends on various factors, the most critical of which is roasting. The roasting of coffee beans is a thermochemical process that enhances the development of the characteristic aromas and flavors found in coffee infusions [2] [3]. The high demand for roasted coffee has led to the development of various roasting techniques that differ in terms of the methods used to apply heat and the types of thermal transfer. The quality of roasted coffee is influenced by the type of roaster, temperature and duration of roasting. Roasting techniques can be divided into conventional and emerging methods. Conventional methods include pan roasting, oven roasting and sand roasting. Emerging techniques include hot-air roasters, superheated steam roasters and Revtech roasters [4].

A significant amount of research has been conducted on coffee roasting. Ozel *et al.* [5] roasted coffee beans using a pan roaster. The results revealed limitations such as poor temperature control, prolonged roasting time, impurity risks and unsanitary conditions leading to nutritional loss. Lee *et al.* [6] compared the roasting of coffee using a pan roaster and a hot air roaster. They found that pan roasting accelerated the formation of α-dicarbonyl compounds, melanoidins and proteins, whereas hot air roasting produced a gentler roast and reduced the activation energy of chemical reactions. However, the formation of these compounds comes at the expense of thermal uniformity and the preservation of sensitive coffee compounds [7]. Fellows [8] used gas-powered oven roasters for coffee beans, achieving uniform heating and faster roasting than with a pan roaster. However, oven roasters generate rapid air flows that may desiccate the beans, alter their texture and affect their shelf life. Kaur *et al.* [9] and Swarnakar *et al.* [10] studied sand roasting for value-added food processing. Their results highlighted challenges such as uneven heat distribution, sand contamination risks, energy inefficiency, low productivity and hygiene issues. According to Chikelu *et al.* [11], conventional methods also expose users to heat and smoke hazards from wood, agro-industrial residues, charcoal and gas combustion, which can lead to nutrient degradation due to poor thermal control. Emerging methods address these limitations. Santoso *et al.* [12] and Freitas *et al.* [13] demonstrated that slow roasting enhances aromas, whereas fast roasting preserves caffeine more effectively. Medium roasting strikes a balance between aroma, flavor, and bitterness. New methods have been developed to overcome the limitations of traditional coffee roasting techniques. Al-Shemmeri *et al.* [14] investigated the porosity of coffee beans during hot air roasting in a fluidised bed roaster at a constant temperature. Their results showed that the porosity of the beans increased by up to 60%. Porosity is closely related to several thermophysical properties, such as density, thermal conductivity, and specific heat capacity.

Suleman *et al.* [15] and Zzaman *et al.* [16] demonstrated reduced roasting time and minimized loss of thermosensitive compounds using superheated steam roasting. Tuncel *et al.* [17] and Bagheri *et al.* [18] employed infrared hot-air roasting, but noted limitations such as shallow radiation penetration and surface sensitivity. Idrus *et al.* [19] studied the superheated steam roasting of peanuts. Their results showed that peanuts roasted with superheated steam yielded more oil than those roasted using conventional methods. In Senegal, the most commonly used methods are oven roasting and stove roasting. Kumoro *et al.* [20] developed a superheated steam spray drying system. The results indicated reduced thermal degradation of nutraceuticals and improved energy efficiency. In Senegal, the most common techniques are oven roasting and pan roasting [21].

These techniques primarily rely on fuels such as wood and butane gas. The combustion of butane gas releases CO_2, which contributes to greenhouse gas emissions. Using firewood results in CO_2 emissions and drives deforestation. Using a renewable energy source offers a promising alternative to fossil fuels and wood for roasting the coffee-Guinea pepper blend. The abundance of cow dung in Senegal makes it ideal for developing waste valorization practices that align with the energy and thermal demands of roasting. In this context, biogas technology could be used as an alternative to wood and butane gas for roasting the blend. Through anaerobic digestion, the biogas sector produces biomethane, which can generate the thermal energy required for roasting this blend [22]. Various types of biodigester have been developed; the most suitable type depends on the waste to be processed, the construction materials used, the cost and the maintenance requirements. Farinet [23] found that Chinese and Indian biodigesters exhibit limited performance. Benaissa [24] and Aboubakar *et al.* [25] reported that fixed-dome digesters produce over 50% biomethane. Similarly, geometric bell models tested by Igoud *et al.* [26] yielded more than 50% biomethane. Camarena-Martinez *et al.* [27] demonstrated that, owing to their flexibility, airtightness and corrosion resistance, geomembrane biodigesters maximize biogas production, reduce carbon footprints, valorize organic waste and require minimal maintenance. These systems are more efficient, economical and sustainable, and can be adapted to handle varying waste volumes.

To address quality and hygiene concerns, superheated steam roasting coupled with a biodigester could be used as an alternative to roasting the coffee-Guinea pepper blend with gas or wood. The objective is to analyze the superheated steam roasting parameters of the blend and characterize the biogas produced. This approach aims to provide a sustainable, local solution for coffee production that makes use of renewable resources and reduces environmental impact. This document is organized as follows. Section 2 presents the measurement devices and the experimental procedure. Section 3 examines the results and discussion.

2. Materials and Methods

2.1. Description of Experimental Setup

This work was carried out at the Center for Studies and Research on Renewable Energy in Hann Bel Air, Dakar, Senegal. The experimental setup for superheated steam roasting of the coffee-Guinea pepper blend comprises a roasting chamber, a steam generator, a superheater heat exchanger and a burner. The burner is powered by biogas from a geomembrane biodigester with a capacity of 4 m^3. The cylindrical glass roasting chamber measures 0.45 m in height and 0.03 m in diameter (see Figure 1). Saturated steam is produced by a generator equipped with a 0.33 L tank and 1300 W of power. This steam is then superheated using a 2 m-long copper coil, which is heated by a biogas-fueled burner. The Arabica coffee beans had an initial moisture content of 11.06%, while the Guinea peppercorns had an initial moisture content of 8.75%. Five coffee beans were introduced into the roasting chamber, where they were in direct contact with the superheated steam to ensure uniform roasting. This small batch was selected as part of a laboratory-scale experimental approach to obtain accurate temperature change and roasting time measurements using integrated thermocouples. Using five beans provides a better understanding of heat transfer mechanisms and thermochemical effects on a small scale. This is a preliminary step to further large-scale tests aimed at validating the reproducibility of the process under industrial conditions. Once roasted, the coffee beans are immediately mixed with the Guinea peppercorns at a ratio of 10%. The residual heat from the coffee beans is then used to roast the peppercorns through simple agitation until the roasting process is complete.

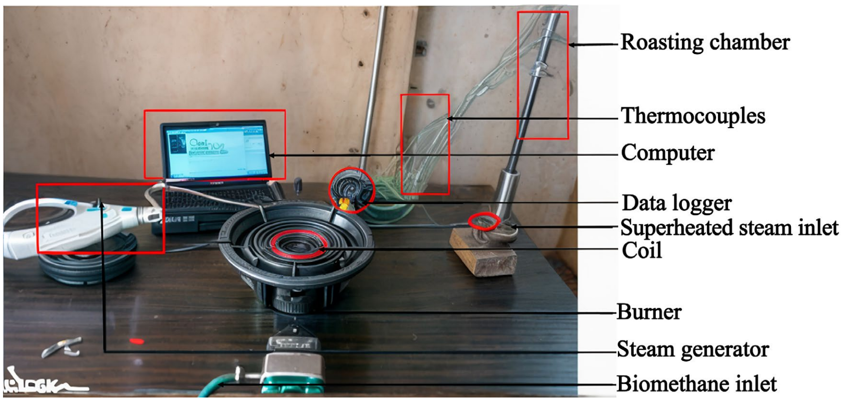

Figure 1. Experimental setup.

2.2. Measurement of Roasting Temperature and Duration

The quality of roasted coffee is highly dependent on roasting temperature and duration. These parameters are meticulously measured using K-type thermocouples installed inside each coffee bean, at the inlet of the superheated steam, and at the outlets of both the roaster and the saturated steam generator. To achieve this, holes measuring 5 mm in depth and 1 mm in diameter were drilled into the green coffee beans, which were then fixed and suspended in the roasting chamber. The data collected by the thermocouples is recorded in real time using a data logger connected to a computer (Figure 2). To minimize uncertainties, this experimental procedure was repeated three times. The roasted beans' properties, including color, temperature evolution, moisture content, and mass loss, are analyzed and correlated with the experimental parameters.

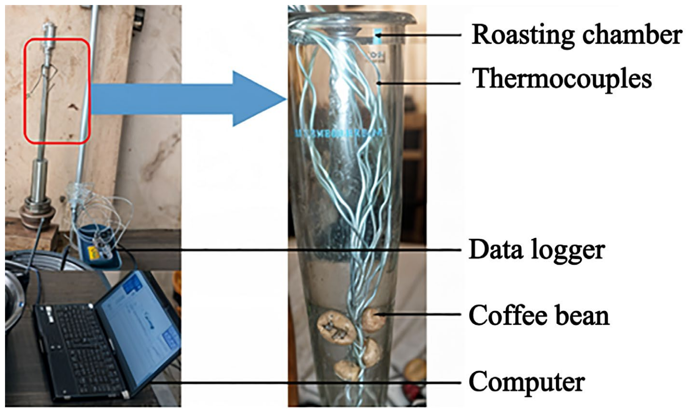

Figure 2. Measurement of roasting temperature and duration.

2.3. Measurement of Moisture Loss in Coffee Beans

The moisture content is analyzed in the laboratory using the oven-drying method based on ASTM D 3172 [28]. This method involves drying the coffee in an oven at 105˚C for 24 hours. After cooling in a desiccator, the mass loss is calculated as a percentage using Equation (1):

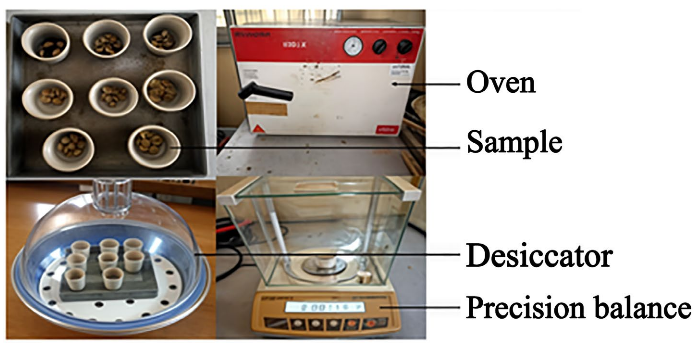

Figure 3. Oven and desiccator used.

$$H(\%) = \frac{m_1 - m_2}{m_1 - m_0} \times 100 \quad (1)$$

m_0: Mass of the empty capsule.

m_1: Mass of the empty capsule plus the sample before drying.

m_2: Mass of the capsule plus the sample after drying.

Figure 3 illustrates the equipment used.

2.4. Measurement of Steam Flow Rate

Three steam flow rates were investigated. These flow rates were experimentally measured based on the known volume of the steam generator tank (0.330 L) and the time required for complete vaporization under three different control knob settings: minimum, intermediate, and maximum.

For a measurement uncertainty on mass $U(m)$ and an uncertainty on time $U(t)$, the uncertainty on the flow rate $U(D)$ is determined using Equation (2).

$$\frac{U(D)}{D}=\sqrt{\left(\frac{U(m)}{m}\right)^2+\left(\frac{U(t)}{t}\right)^2} \tag{2}$$

For a water mass of 330 g with $U(m) = \pm 1$ g, $U(t) = \pm 1$ s, D steam flow rate and a duration of 825 s:

$$\frac{U(m)}{m}=\frac{1}{330}=0.00303 \tag{3}$$

$$\frac{U(t)}{t}=\frac{0.0167}{13.75}=0.00121 \tag{4}$$

$$\frac{U(D)}{D}=\sqrt{0.00303^2+0.00121^2}=0.00327 \tag{5}$$

$$U(D)=24\times 0.00327 \tag{6}$$

$$D=24\pm 0.08\ \text{g/min} \tag{7}$$

The same approach was applied to the intermediate and maximum settings, yielding flow rates of 27 ± 0.09 g/min and 30 ± 0.10 g/min, respectively.

2.5. Characterization of the Biodigester

Cow dung was used as the raw material for the biodigester. It was collected in 50 kg bags and 25 L containers after the slaughter of cows. The feeding of the biodigester was carried out in two stages. On the first day, eight 25 L containers of liquid substrate were introduced into the biodigester. On the second day, 507.48 kg of solid substrate were mixed with 216.5 L of water and added. After filling and hermetic sealing, the temperature, pH and chemical composition of the biogas were regularly monitored. These characteristics were analyzed using a G5000 biogas analyzer connected to the biodigester (Figure 4). The indoor and outdoor temperatures were measured using a Fourier transform infrared spectroscopy (FTIR) T420 thermal imaging camera (Figure 5). To ensure a continuous and stable supply, the biogas was stored in balloons. A water trap was connected to the biodigester to minimize moisture content during combustion. The hydrogen sulfide (H_2S) content was reduced using an H_2S purifier (Figure 6).

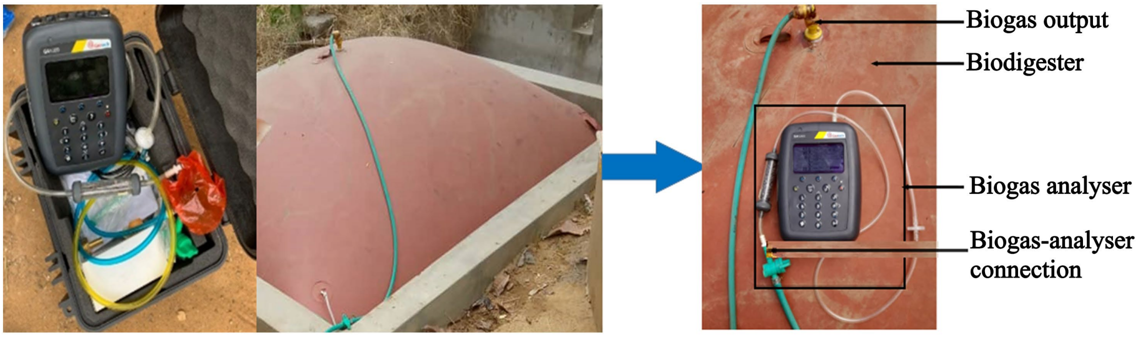

Figure 4. Biogas characterization

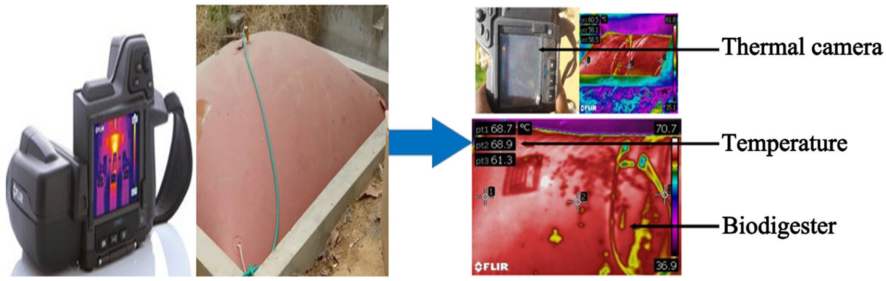

Figure 5. FLIR T420 thermal camera.

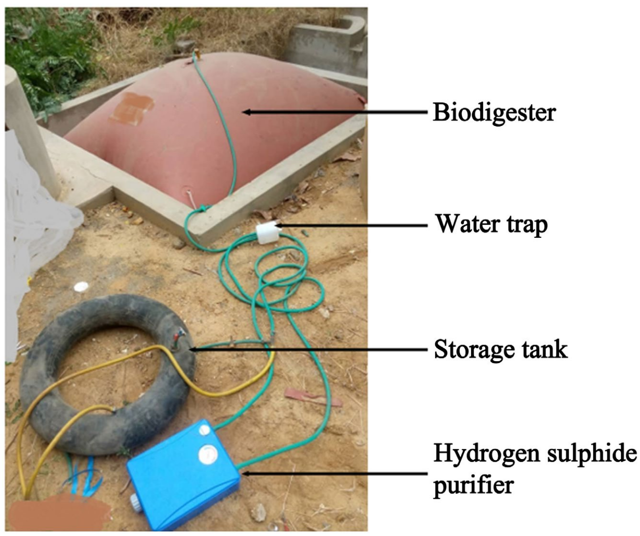

Figure 6. Biogas storage.

3. Results

3.1. Biogas Production

Monitoring biogas production helps evaluate the efficiency of the biodigester based on its temperature and the composition of the biogas produced. The internal temperature ranges from 38˚C to 72.9˚C, indicating mesophilic and thermophilic phases conducive to anaerobic digestion. The temperature evolution (Figure 7) shows a rapid initial increase, followed by fluctuations influenced by external conditions.

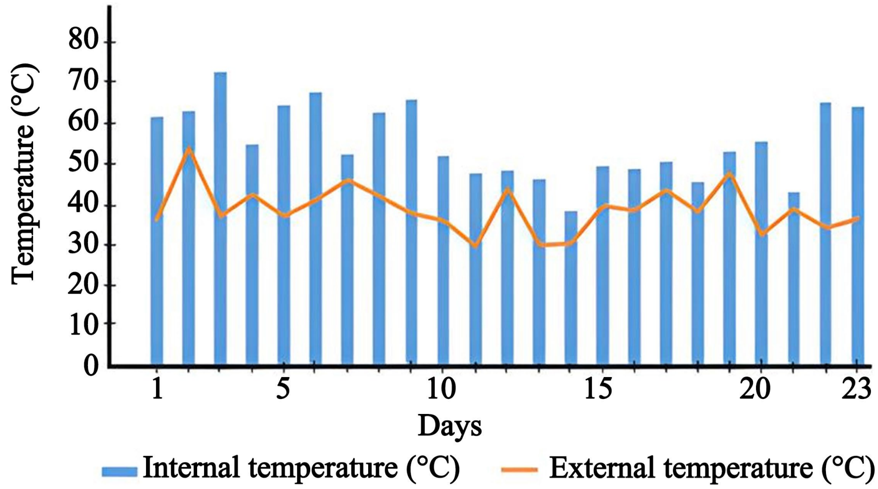

Figure 7. Evolution of indoor and outdoor temperatures over time.

Analysis of biogas composition (Figure 8) reveals a gradual increase in CH_4 concentration from 29% to 59.1% by the thirteenth day, indicating optimal conditions for methanization. The transformation of volatile acids reduces CO_2 concentration, while CO and H_2S levels remain low, necessitating appropriate management.

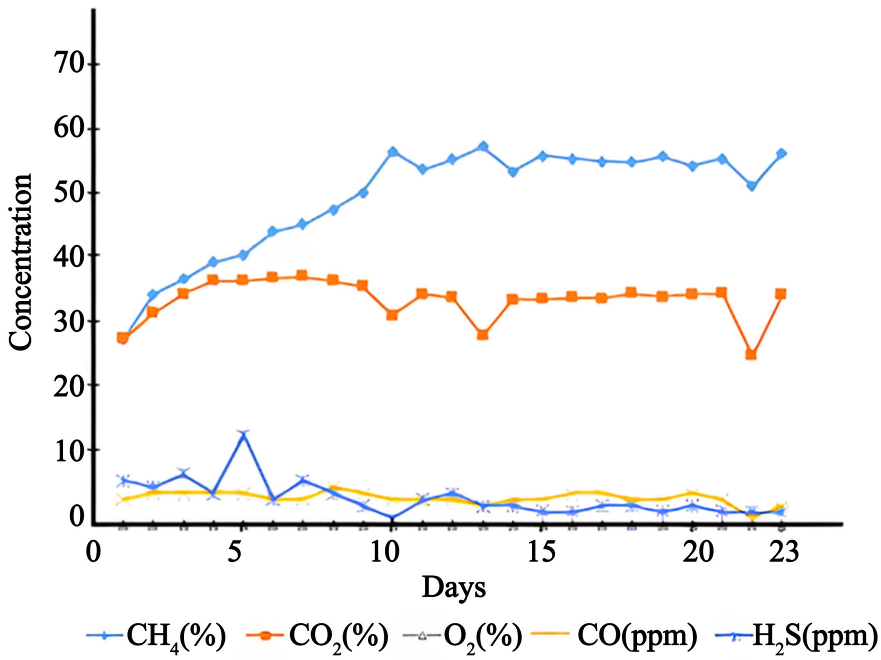

Figure 8. Evolution of gas components over time.

The statistical analysis of methane content, as summarized in Table 1, indicates a mean value of 52% (±9%) with a relatively narrow 95% confidence interval (±3.9%). These results provide evidence of the biodigester's stable and efficient performance.

Table 1. Mean, standard deviation, and 95% confidence interval (±CI) of methane content.

Parameters	Values
Mean (%)	52
Standard deviation (%)	9
IC 95% (±%)	3.9

3.2. Operating Parameters of Biodigester

Based on the total 740 L of substrate introduced and the experimental conditions, the hydraulic retention time (HRT) ranges between 5 and 7 days. This duration corresponds to a batch feeding test phase, which is typical of laboratory-scale experiments. Mudhoo *et al.* [29] reported that under mesophilic/thermophilic conditions, one kilogram of fresh manure produces an average of 0.22 m^3 of biogas. However, for an introduced mass of 507.48 kg, the total volume of biogas produced is estimated at 112 m^3 over an active period of approximately 20 days. This results in an average daily yield of 5.6 m^3/day, of which about 3.3 m^3/day is methane (at 59.1% CH_4). These performances confirm the biodigester's ability to supply the thermal energy required for superheated steam production. Increasing the substrate volume or adopting continuous feeding would meet the energy needs of a medium-scale artisanal roasting unit.

3.3. Biogas Combustion Test

The biogas produced is a mixture of combustible gases with a methane (CH_4) content of 59.1%, exceeding the minimum threshold (50% - 55%) required for stable combustion. A flammability test was conducted using an atmospheric burner (see Figure 9). Combustion is characterized by the emission of a blue flame, which confirms the presence of methane in a significant proportion greater than 50%.

Figure 9. Biogas combustion test.

3.4. Evolution of Roasting Temperatures

3.4.1. Saturated and Superheated Steam Temperatures

Figure 10 illustrates the evolution of saturated steam and superheated steam temperatures measured upstream of the beans over time. The average measured temperature of the superheated steam is 284˚C. The temperature of the saturated steam is relatively stable, oscillating slightly around an average of 107˚C. This reflects a controlled process in the generator where the steam reaches its saturated state at a constant temperature. The steam produced circulates through a coil exchanger where it is re-superheated by the burner, resulting in a significant increase in steam temperature.

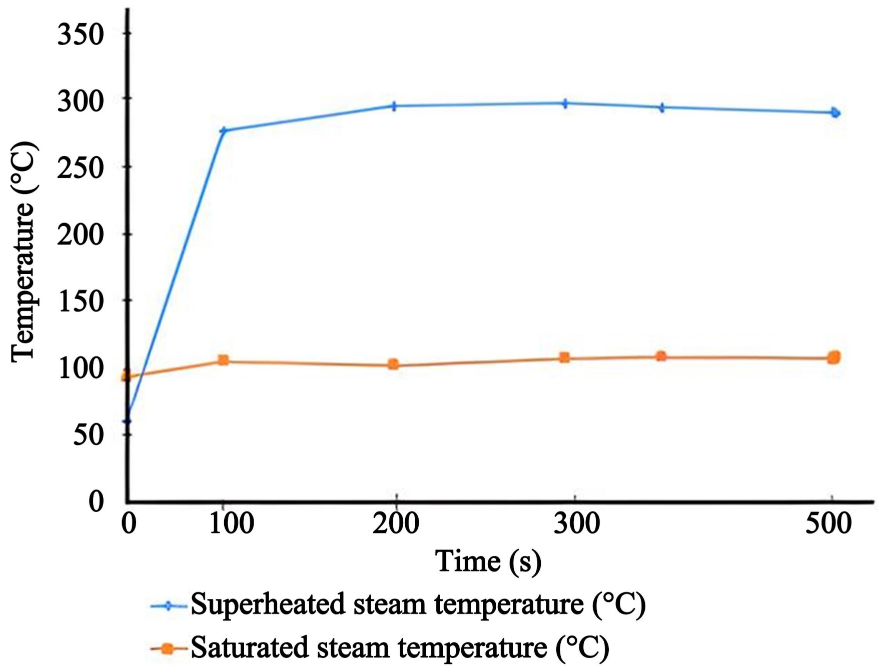

Figure 10. Evolution of superheated and saturated temperature.

3.4.2. Evolution of Coffee Bean and Superheated Steam Temperatures

The thermal profile analysis during roasting reveals a progressive increase in coffee bean temperature, directly correlated with their heat absorption capacity. Initial fluctuations, attributed to factors such as bean position within the roasting chamber, particle size, and residual moisture content, momentarily affect this progression. However, the slight temperature differences observed between the beans gradually decrease, leading to a satisfactory thermal uniformity by the end of the process. At the target temperature of 250˚C, the beans undergo full aromatic development, ensuring a uniform and consistent roast. Figure 11 illustrates the temporal evolution of superheated steam temperatures at the inlet and outlet of the roasting chamber, as well as the corresponding coffee bean temperature profile.

The calculation of the mean, standard deviation, and confidence interval allows for the statistical characterization of coffee bean temperatures during roasting. This statistical analysis makes it possible to assess the stability, thermal uniformity, and reproducibility of the roasting process. To avoid dispersion caused by the initial temperature rise, only temperatures ≥ 200˚C were considered, as presented in Table 2.

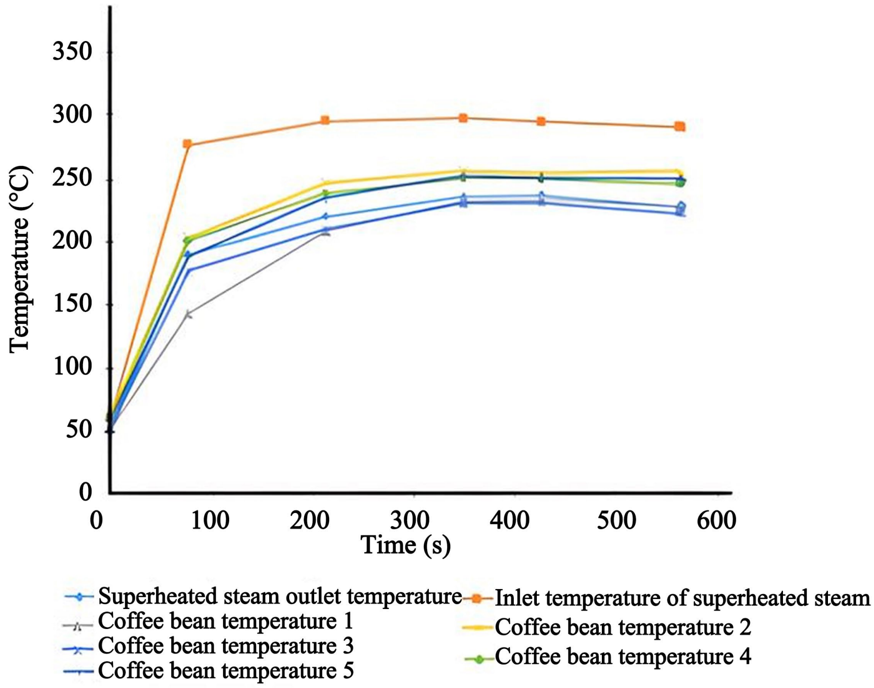

Figure 11. Evolution of the temperatures of the superheated steam at the entrance and exit of the roasting chamber and of the coffee beans over time.

Table 2. Mean, standard deviation, and 95% confidence interval (±CI) of temperatures for each coffee bean.

Coffee bean	Mean	Standard deviation (%)	IC 95% (±%)
Coffee bean_1	234	15.3	13.9
Coffee bean_2	242.5	18.6	16
Coffee bean_3	236.4	13.5	12.2
Coffee bean_4	139.8	17	15.4
Coffee bean_5	240.2	14.8	13.4

The results indicate that coffee bean temperatures remained both homogeneous and stable, exhibiting variations of less than 10˚C between individual beans and moderate confidence intervals (±12 to ±17˚C). These findings provide strong evidence of the thermal stability and reproducibility of the roasting process.

Figure 12 illustrates the uniformly roasted coffee beans.

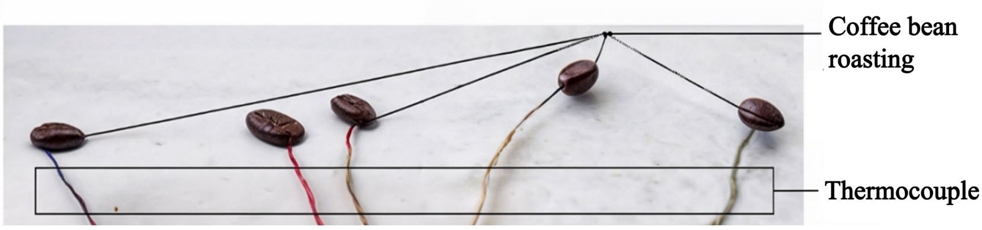

Figure 12. Roasted coffee beans.

3.4.3. Influence of Steam Flow Rate on Roasting Dynamics

A comparative study of three steam flow rates (24 g/min, 27 g/min, and 30 g/min) highlights the critical impact of this parameter on process efficiency. Figure 13 illustrates the temperature evolution of the coffee beans for each steam flow rate.

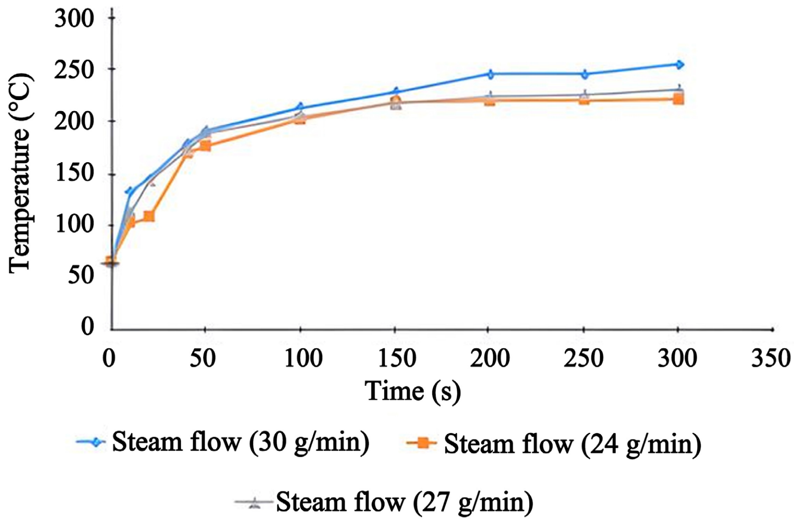

Figure 13. Evolution of coffee bean temperature as a function of steam flow rate.

3.5. Dynamics of Moisture Loss during Roasting

The moisture loss curve of coffee beans, measured during roasting, is divided into three distinct phases, each reflecting the product's physicochemical transformations. During the initial drying phase (0 to 150 seconds), the moisture content of the beans decreases from 11.06% to 7.08%, corresponding to the removal of surface free water. It is followed by the actual roasting phase (150 to 310 seconds), during which the moisture content further decreases to 4.67%, accompanied by the first crack, caused by the expansion of the beans under heat. The final phase (310 to 610 seconds), marked by a second crack, sees the residual moisture reach

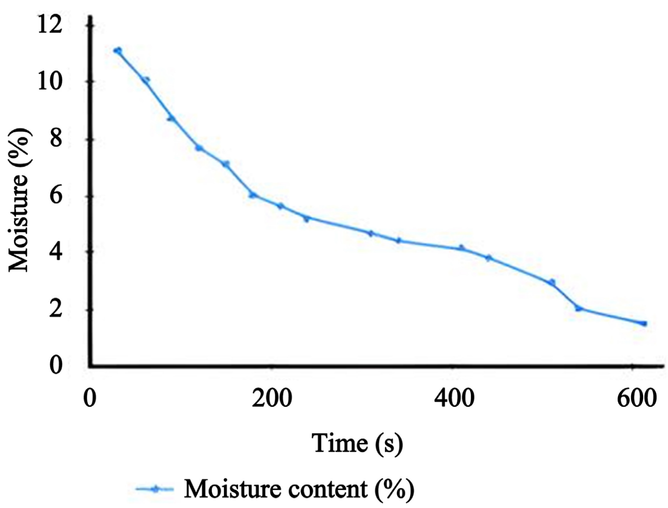

Figure 14. Moisture loss of coffee beans.

1.5%. Figure 14 illustrates the moisture loss of the coffee beans throughout the roasting process.

The statistical analysis of moisture loss in the beans, as shown in Table 3, indicates a consistent decrease in moisture content from 11.06% to 1.5%, with a mean value of 5.65% ± 2.8%, confirming its consistency and reproducibility.

Table 3. Mean, standard deviation, and 95% confidence interval (±CI) of coffee bean moisture content.

Parameters	Values
Mean (%)	5.65
Standard deviation (%)	2.80
IC 95 % (± %)	1.54

3.6. Evolution of the Color of Coffee Beans

The most commonly used measure to determine the degree of roasting is the color of the bean. Roasting occurs in five stages: drying, yellowing, the first crack, roast development, and the second crack. Figure 15 illustrates the development of bean color during the different roasting stages.

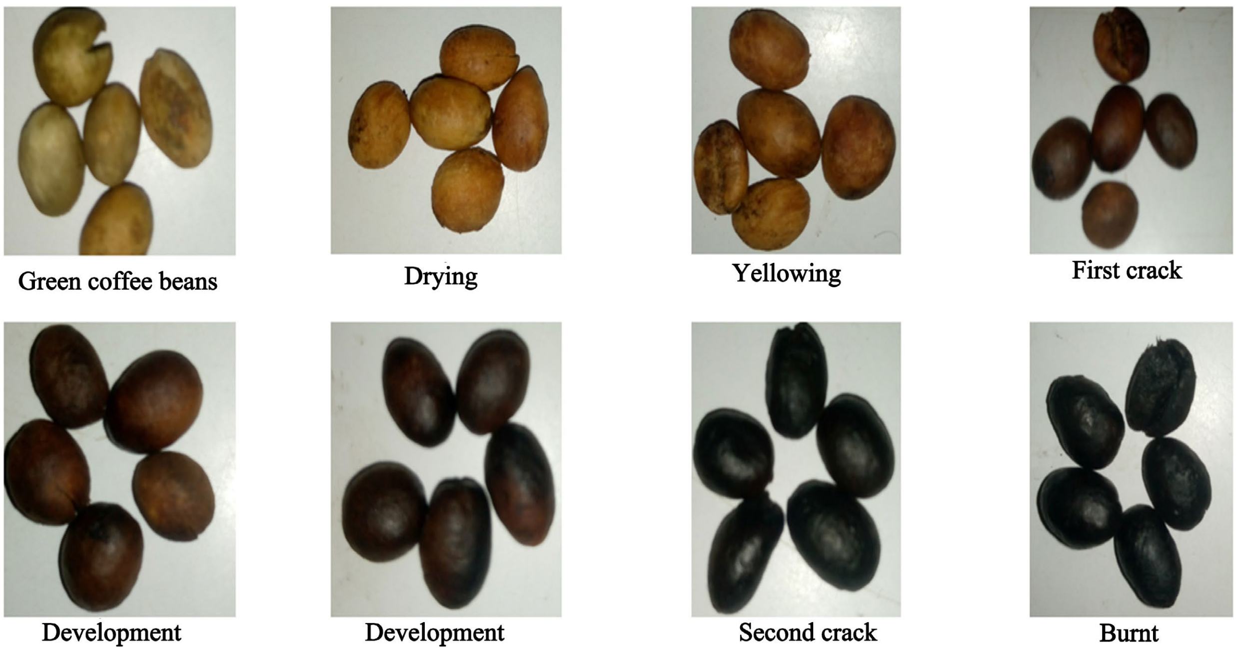

Figure 15. Evolution of the color of the beans during roasting.

3.7. Roasting of Guinea Pepper

The blending of coffee and Guinea pepper is carried out immediately after roasting the coffee beans. The residual heat from the freshly roasted coffee beans is used to roast the Guinea peppercorns by simply stirring the roasted coffee and pepper mixture until it reaches the desired roasting level. The results showed a moisture loss in Guinea peppercorns from 8.75% to 3.23%. This significant decrease in moisture, corresponding to a loss of 5.52%, results from heat transfer between the freshly roasted coffee beans and the Guinea peppercorns during blending. The thermal energy causes rapid evaporation of water from the peppercorns, facilitated by their structure, which promotes moisture release in the form of steam. Figure 16 illustrates the roasted coffee-Guinea pepper mixture.

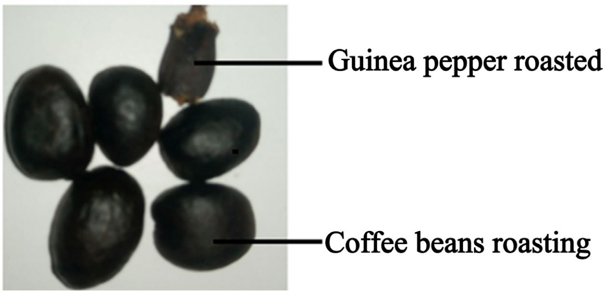

Figure 16. Roasted coffee-guinea pepper mixture.

3.8. Effect of Roasting on the Aromatic Profile of the Coffee-Guinea Pepper Blend

The roasted coffee-Guinea pepper blend is prepared using coffee beans roasted to the second crack, an advanced stage of roasting where aromatic compounds are highly developed. The infrared spectra shown in Figure 17 reveal heightened carbonyl and aromatic bands, indicating a strong presence of pyrazines, furfural, and aldehydes. This aromatic richness from the coffee is complemented by compounds in the roasted pepper, such as phenols and terpenes.

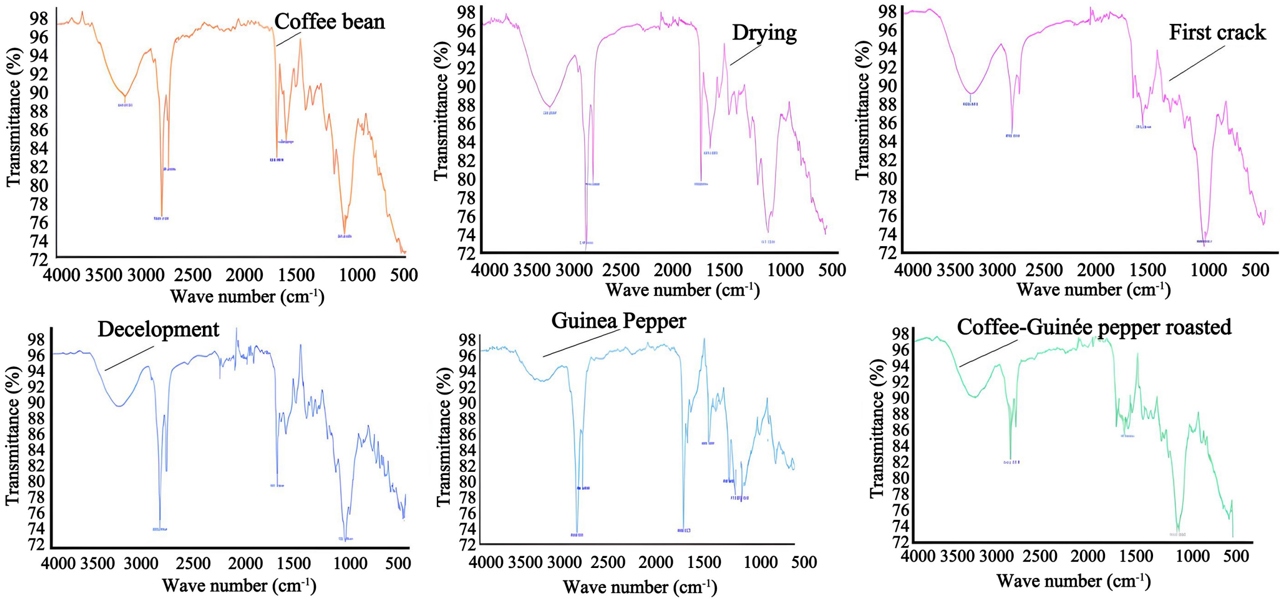

Figure 17. Infrared spectra of the coffee roasting phases.

Table 4 illustrates the influence of roasting phases on the aromatic profile.

Table 4. Influence of roasting phases on the aromatic profile.

Roasting phase	Temperature	Chemical transformation (IR spectrum)	Effects on aromatic profile
Green coffee	<100˚C	High content of -OH groups, high moisture	Neutral aromas, no sensory complexity
Drying	100˚C - 150˚C	Moisture reduction, onset of thermal degradation	Slight development of mild notes
Development	150˚C - 190˚C	Appearance of C=O, ketones, onset of Maillard reactions	Sweet and floral aromas
First crack	190˚C - 220˚C	Formation of pyrazines, furfural, and volatile compounds	Roasted, nutty, and caramel notes
Second crack	220˚C - 250˚C	Enhancement of aromatic bands, partial carbonization	Intense notes (smoky, cocoa, woody), full-bodied
Roasted guinea pepper	Heat from coffee beans	Formation of oxidized terpenes and light phenols	Mellowed peppery aromas, smoky notes
Coffee-pepper blend	Coffee (second crack) + roasted pepper	Intense overlap of IR spectral signatures	Robust, spicy, and complex profile with lasting mouthfeel

3.9. Comparative Analysis between Traditional Roasting and Superheated Steam Roasting

Control experiments using traditional roasting methods were indeed conducted for comparative purposes, as illustrated in Figure 18. This figure displays the infrared (IR) spectra of the coffee-Guinea pepper blend roasted using the traditional method and superheated steam roasting.

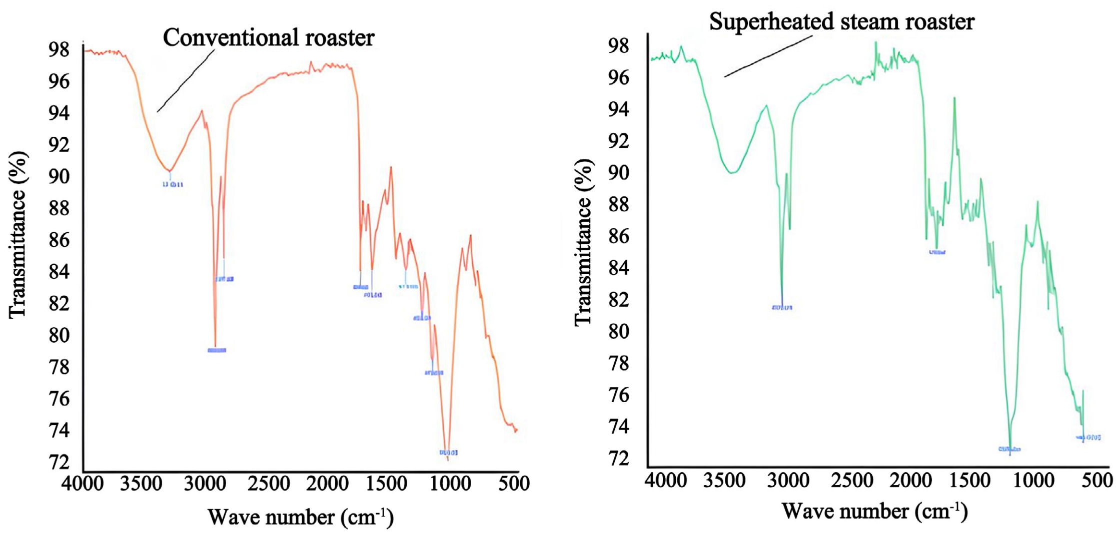

Figure 18. Infrared spectra of conventional vs. superheated steam roasting for the coffee-Guinea pepper blend.

3.10. Spectroscopic Analysis of Chemical Transformations Induced by Roasting in the Coffee-Guinea Pepper Blend

The spectra obtained by Fourier transform infrared spectroscopy (FTIR) reveal that the roasting of the coffee-Guinea pepper blend induces significant changes in its chemical composition. The attenuation of bands associated with volatile groups

C=O around 1740 cm^{-1}, O-H around 3295 cm^{-1}, and C-H around 2924 cm^{-1} indicates the thermal degradation of fatty acids, alcohols, and terpenes initially present in green coffee and Guinea pepper. Simultaneously, new bands appear around 1620 cm^{-1}, corresponding to condensed aromatic structures, and in the 1000 - 1300 cm^{-1} range, attributed to secondary volatile compounds resulting from thermal transformation processes. Figure 19 illustrates the changes in chemical composition before and after roasting.

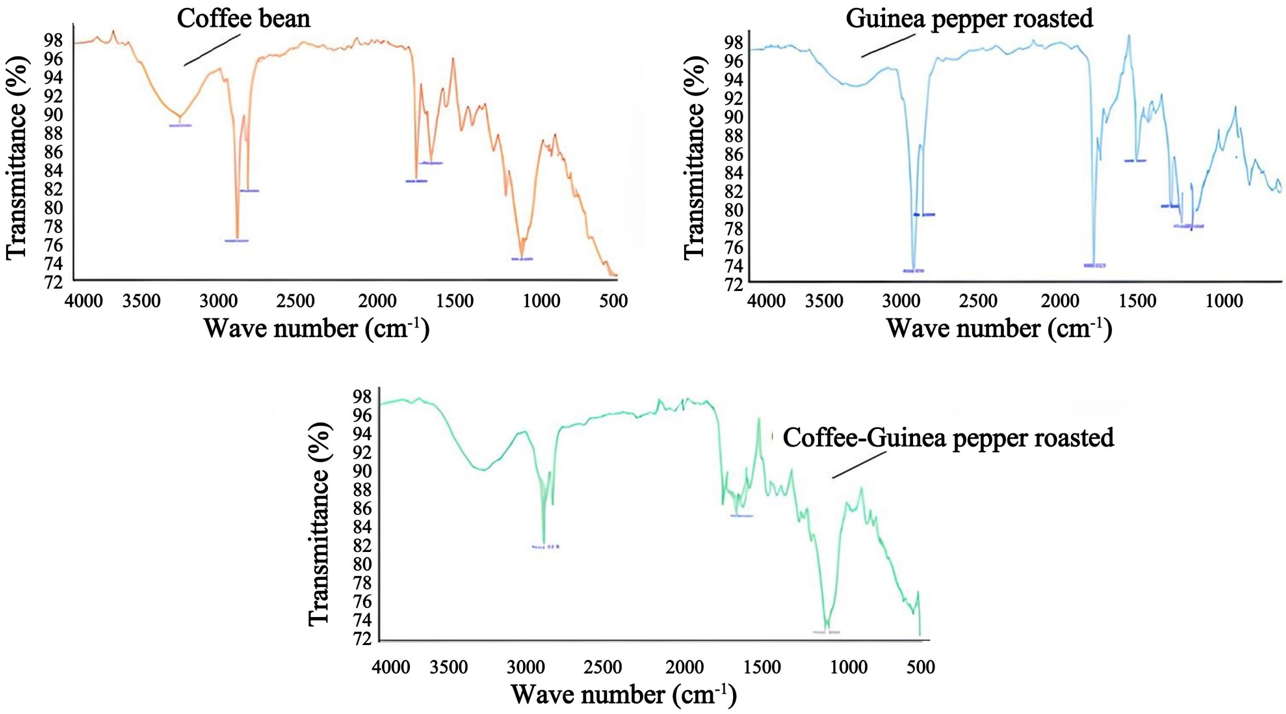

Figure 19. Changes in chemical composition before and after roasting.

3.11. Sensory Analysis of Roasted Coffee

The sensory characteristics of the roasted coffee-Guinea pepper blend produced using superheated steam were compared to two samples roasted using the conventional method. For each sample, 20 g of ground coffee was filtered with 258.7 mL of hot water, followed by the addition of 46 g of sugar. Figure 20 illustrates the filtered beverage samples.

Figure 20. Brewed beverage of the coffee-Guinea pepper blend roasted with superheated steam (a), and using the conventional method (b) and (c).

For each sample, five panelists provided their evaluation of color and aroma intensity. Figure 21 illustrates the tasting process.

Figure 21. Tasting.

Analysis of the evaluations from the five panelists reveals a clear superiority of the superheated steam roasting method compared to conventional methods. As shown in Table 5, superheated steam roasting received significantly higher average scores across all sensory criteria.

Table 5. Ratings from five tasters.

Roasting method	Color (average/10)	Aromatic intensity (average/10)	Overall rating (average/10)
Superheated steam roasting	8	7.6	7.8
Traditional method 1	6	5.6	5.8
Traditional method 2	4.8	4.4	4.6

The sensory analysis, conducted alongside physicochemical measurements, established a correlation between the molecular characteristics revealed by FTIR spectra and the sensory perception of the roasted coffee.

Superheated steam roasting was distinguished by a visibly darker color and a significantly higher aromatic intensity. These observations were confirmed by FTIR results, which showed better preservation of key functional groups such as C=O, C-H, and C-O—essential to the aromatic and flavor profile of coffee.

From a sensory standpoint, the panelists assigned an overall score of 7.8 to the superheated steam-roasted coffee, compared to 5.8 for the conventionally roasted sample. The correlation between the darker color (+33%) and enhanced aromatic intensity (+36%) with overall satisfaction highlights a clear qualitative advantage of this method. These findings support the hypothesis that the gentle and uniform roasting induced by superheated steam allows for a gradual release of aroma compounds without excessive thermal degradation, which is in perfect agreement with the FTIR spectroscopic signature observed.

3.12. Comparison between Superheated Steam Roasting and Air Roasting

Our experimental work on superheated steam roasting of coffee was compared with the results of Bottazzi *et al.* [30]. Figure 22 and Figure 23 illustrate the evolution of temperature and moisture losses over time, as well as the analysis of the linearity of the result.

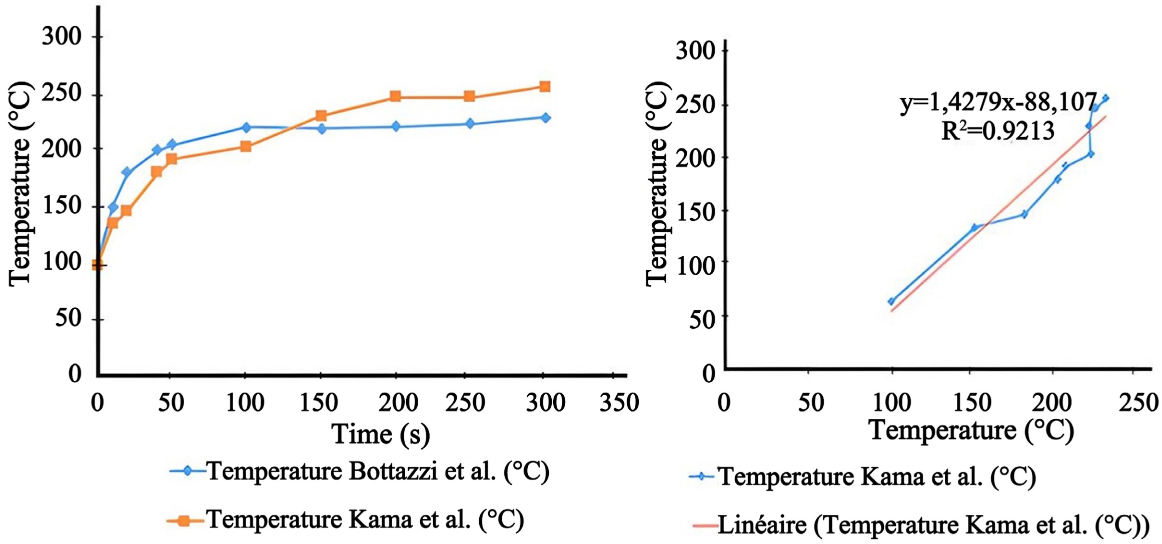

Figure 22. Coffee bean temperature compared to the experimental results of Bottazzi *et al.* [30].

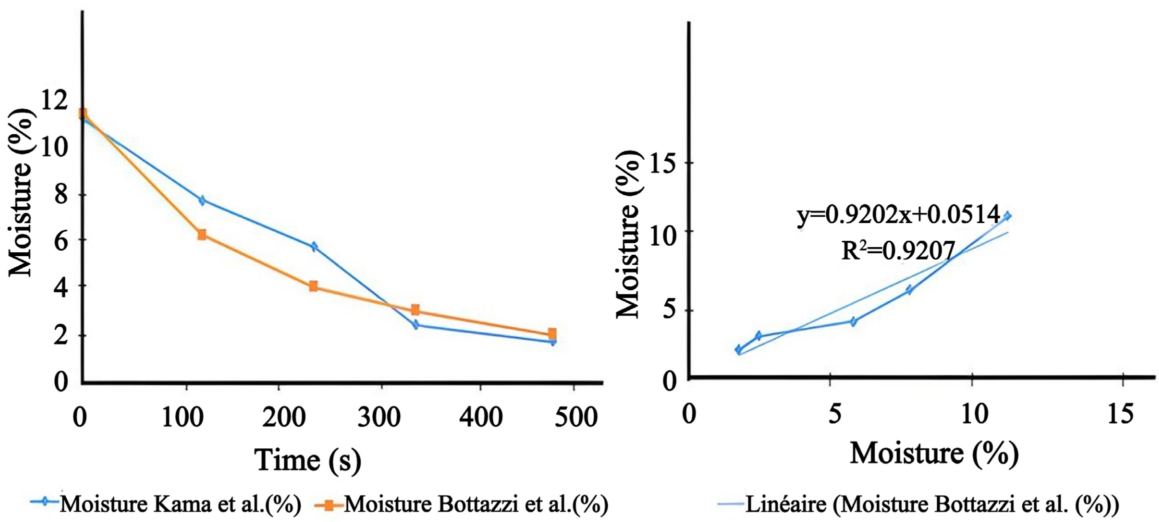

Figure 23. Moisture content compared to experimental results for Bottazzi *et al.* [30].

3.13. Quantitative Calculations of Energy and CO_2 Savings

The five roasted coffee beans correspond to a mass of 25 g. For a daily production of 5.6 m^3 of biogas, including 3.3 m^3/day of CH_4, roasting with superheated steam at 250˚C for 450 seconds was carried out. This roasting duration and temperature were achieved using 0.03 m^3 of biogas characterized by a CH_4 content of 59.1%, corresponding to an average lower heating value (LHV) of 21 MJ/m^3. Under these conditions, the energy consumed is:

$$E = \frac{0.03 \times 21}{0.025} \tag{8}$$

$$E = 25.2\ \text{MJ/kg} \tag{9}$$

$$E = \frac{25.2}{3.6} \tag{10}$$

$$E = 7\ \text{kWh/kg} \tag{11}$$

In terms of CO_2 emissions, the combustion of methane (CH_4) produces CO_2 according to the stoichiometric reaction:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{12}$$

The CO_2 emitted from the combustion of 0.03 m^3 of biogas (containing 59.1% CH_4) is estimated as follows:

$$V(CH_4) = 0.03 \times 0.591 = 0.01773\ \text{m}^3 \tag{13}$$

$$CO_2\ \text{emis} = 0.01773 \times 1.9 \tag{14}$$

$$CO_2\ \text{emis} = 0.0337\ \text{kg}\ CO_2 \tag{15}$$

For 1 kg of coffee, the corresponding emission is calculated as:

$$CO_2\ \text{emis} = \frac{0.0337}{0.025} \tag{16}$$

$$CO_2\ \text{emis} = 1.35\ \text{kg}\ CO_2/\text{kg coffee} \tag{17}$$

Furthermore, according to Rahman *et al.* [31], the net CO_2-eq emissions from biogas combustion are significantly lower, approximately 0.043 kg CO_2-eq/m^3, since biogenic CO_2 is not accounted for in the carbon footprint.

Thus, the emissions associated with 0.03 m^3 of biogas are:

$$0.03 \times 0.0043 = 0.00129\ \text{kg}\ CO_2\text{-eq} \tag{18}$$

$$CO_2\ \text{emis} = \frac{0.00129}{0.025} \tag{19}$$

$$CO_2\ \text{emis} = 0.0516\ \text{kg}\ CO_2\text{-eq/kg coffee} \tag{20}$$

Compared to the findings of Tsai *et al.* [32] (0.1576 kg CO_2/kg), our roasting technology demonstrated an 11.22% reduction in energy consumption and a 67% reduction in CO_2 emissions. These results indicate that the proposed technology is a clean, sustainable energy alternative well-suited to the context of sustainable development.

4. Discussion

4.1. Changes in Temperature and Composition of Biogas over Time

The observed temperature (**Figure 7**) variations highlight the biodigester's ability to reach and maintain optimal thermal conditions for bacterial activity. The rapid initial temperature increase indicates effective heat retention, while the fluctuations reflect the influence of climatic conditions. The system's insulation ensures stable thermal conditions, optimizing bacterial activity and improving biogas production. This thermal stability is essential for sustaining the activity of mesophilic and thermophilic bacteria, which is critical to the overall efficiency of biogas production. The results in **Figure 8** show an increase in methane content. This evolution of methane is due to thermal conditions that are favorable to methanogenic bacteria. The decrease in CO_2 and the consistently low levels of CO and H_2S also indicate good substrate conversion and a limited presence of toxic byproducts. The effective management of these components, which characterize the biogas, ensures the safety and durability of the biodigester. These results confirm the proper functioning of the system and the production of high-quality biogas.

4.2. Biogas Combustion

Biogas combustion test (**Figure 9**) demonstrates the ability of the biogas and burner to superheat the saturated steam required for roasting the coffee-Guinea pepper blend. The resulting blue flame indicates efficient combustion, confirming that the biogas is of high quality and suitable for thermal applications. The methane content exceeding the 50% threshold further confirms the efficiency of the digestion process and the quality of the biogas, highlighting the potential of the biodigester for energy recovery in agri-food processes.

4.3. Thermal Performance

The slight variations observed (**Figure 10**) are the result of manual handling of the saturated steam generator. The produced steam circulates through a coil heat exchanger, where it is reheated by the biogas burner. This reheating leads to a significant increase in steam temperature, demonstrating the efficiency of the biogas burner. The fluctuations in the superheated steam temperature, although less pronounced after the initial peak, indicate active regulation of the burner to maintain the temperature required for roasting the coffee and Guinea pepper blend. These thermal performances highlight that the biogas burner is well-suited for the roasting process.

4.4. Temperature of Coffee Beans and Superheated Steam in the Roaster

Superheated steam plays a central role in this mechanism by transferring thermal energy primarily through convection and conduction. A portion of this energy is used to vaporize the residual moisture within the beans, leading to a slight decrease in steam temperature at the roasting chamber outlet. However, this phenomenon is effectively managed through the stabilization of the heat flux, ensuring precise control over the roasting conditions. The system's energy efficiency is further enhanced by high-performance chamber insulation, which minimizes heat losses and enables rigorous thermal regulation. Although residual temperature variations among individual beans persist, they remain negligible and do not compromise the final product quality, as demonstrated by the uniformly roasted beans in the experimental results.

4.5. Superheated Steam Flow Rate on Roasting Dynamics

A flow rate of 24 g/min (**Figure 13**), while economical in steam consumption, significantly restricts heat transfer to the beans, extending the roasting duration and increasing the risk of incomplete roasting, which hinders aroma development. At 27 g/min, the temperature rise accelerates; however, persistent thermal inertia delays the achievement of optimal conditions. Conversely, a 30 g/min flow rate facilitates a rapid and uniform temperature increase, reaching the required 250˚C in a shorter time. This flow rate not only enhances roasting uniformity but also preserves the coffee's organoleptic properties by minimizing prolonged exposure to intermediate temperatures. These findings emphasize the necessity of sufficient energy input to ensure efficient and reproducible roasting while improving the overall system efficiency.

4.6. Moisture Loss

These three phases illustrate the moisture loss in coffee beans during the roasting process (**Figure 14**). The initial drying phase is characterized by uniform heat penetration, which helps prevent irregularities in bean coloration and ensures the development of the characteristic coffee aroma. During the cracking phase, the moisture content in the beans gradually decreases, while sugar caramelization and Maillard reactions take place, defining the distinctive sensory qualities of roasted coffee. The observed transformations, closely linked to temperature and roasting duration, highlight the balance between moisture removal and the preservation of aromatic compounds, which is essential for producing a high-quality final product.

4.7. Color of Coffee Beans during Roasting

Coffee roasting follows a complex process divided into several essential steps to achieve the desired flavor profile (**Figure 15**). It begins with the drying phase, where the green beans lose their moisture and gradually change color from light green to dark brown. During roasting, the beans slightly increase in volume, causing a cracking sound characterized by a silvery skin and the release of small balls. At this point, the first crack occurs due to the heat, causing an increase in internal gas pressure, which leads to the cracking of the beans. This phenomenon is accompanied by a distinct noise that signals the beginning of the development of coffee aromas. During this period, roasting can be adjusted or stopped according to the desired profile, as the temperature of the beans rises more slowly despite constant heat. After the first crack, the development of the beans continues, influencing their balance between acidity and bitterness. A longer roast reduces acidity while increasing bitterness. Continuing the process leads to a second crack beyond 200˚C. At this stage, the oils from the beans appear on the surface, and an intense flavor due to carbonization is characterized by the release of smoke. This step results in the loss of subtle flavors, giving the coffee a robust but less refined taste.

4.8. Roasted Guinea Pepper

This moisture loss in Guinea pepper contributes to their roasting, enhancing their characteristic taste and aroma. The residual moisture content of 3.23% in the roasted Guinea pepper supports preservation by limiting the risk of mold or degradation. This process optimizes the use of the heat generated by the coffee beans without requiring additional energy input, making it both efficient and well-suited for sustainable production.

4.9. Impact of Roasting on the Aromatic Profile of Coffee-Guinea Pepper Blend

The analysis of **Figure 17** confirms that roasting coffee up to the second crack significantly enhances its aromatic complexity, primarily due to the development of pyrazines and furfural, as evidenced by the pronounced carbonyl and aromatic bands in the IR spectra of **Figure 17**. The addition of roasted Guinea pepper further enriches this profile with terpenes and oxidized phenols, contributing subtle peppery and smoky notes. The comparison of IR spectra highlights key evidence validating the efficacy of superheated steam roasting. Both curves exhibit bands around 2923 cm^{-1} (C-H bonds) and 1027 - 1043 cm^{-1} (C-O bonds), indicating the preservation of aromatic functional groups and volatile components in the blend. This demonstrates that superheated steam induces chemical transformations comparable to those of traditional roasting. The superheated steam spectrum shows enhanced retention of intensity in specific characteristic bands, suggesting more effective preservation of aromatic compounds. This reflects a more uniform and less destructive thermal treatment. Superheated steam roasting is significantly faster, reducing energy consumption while ensuring sufficient product transformation, a key indicator of efficiency. The absence of bands indicating excessive decomposition (e.g., in the 1600 - 1700 cm^{-1} range or below 800 cm^{-1}) for superheated steam points to reduced carbonization or degradation of organic structures.

The effectiveness of superheated steam roasting is confirmed by:

- Preservation of key aromatic signatures;
- Reduced processing time;
- Lower thermal degradation.

While achieving results comparable to traditional methods, as demonstrated by the IR spectra. These findings support the viability of this approach for roasting the coffee-Guinea pepper blend, combining efficiency with minimal structural compromise. In addition to this chemical analysis, the energy consumption of biogas-powered superheated steam roasting proves to be significantly lower and more efficient overall compared to conventional roasting processes using wood or butane gas. This method delivers superior overall energy efficiency, attributed to its enhanced heat transfer and reliance on renewable energy sources.

4.10. Thermal Comparison between Hot Air and Superheated Steam Roasting

Bottazzi *et al.* [30] used a hot air roaster with temperatures ranging from 220˚C to 260˚C. The results show similar trends in terms of temperature development. During the drying phase, steam reaches 150˚C in 100 seconds, compared to 130˚C for hot air, due to more efficient heat transfer through conduction and convection. Hot air, by contrast, relies solely on convection. During roasting, temperatures converge between 180˚C and 200˚C between 150 and 200 seconds. However, steam attains the critical temperature threshold faster, reflecting superior thermal penetration. Beyond 200 seconds, steam temperature exceeds 250˚C more rapidly and stabilizes at a higher level. The linear regression curve, with an R^2 value of 0.9213 (**Figure 20**), indicates a strong correlation between measured data, confirming the method's reliability. A maximum temperature difference of 5˚C, corresponding to a relative error of 2.04%, was observed between this experimental study (250˚C) and the reference (245˚C) [29]. This discrepancy is attributed to manual steam flow control and the inherent limitations of thermocouples (±1.5˚C). Superheated steam, with a heat capacity of 2 kJ/kg·K, reaches 250˚C in 450 seconds, compared to 600 seconds for hot air (1.005 kJ/kg·K), while maintaining a maximum temperature deviation of 5˚C. This method reduces residual moisture to 1.5% (vs. 2.5% for hot air) and operates in a low-oxygen environment, minimizing aromatic compound losses. Superheated steam roasting emerges as a reliable, sustainable solution for large-scale production, delivering performance consistent with prior research. Its efficiency in heat transfer, temperature control, and reduced energy consumption positions it as a superior alternative to conventional hot-air methods.

5. Conclusion

Improving the quality of the roasted coffee and Guinea pepper blend is essential for its industrialization. Superheated steam roasting could enhance the quality, taste and aroma of the blend. This experimental study focuses on the superheated steam roasting of the coffee-Guinea pepper mixture powered by a biogas furnace from a geomembrane biodigester. Results show that the biodigester reached a methane content of 59.1% by the 13th day, enabling production of superheated steam at 250˚C. This target temperature was achieved in 450 seconds, with excellent thermal uniformity between the coffee beans (maximum temperature difference of 5˚C). The moisture content of the coffee beans decreased from 11.06% to 1.5%, and that of the Guinea pepper from 8.75% to 3.23%, thanks to residual heat from the roasted coffee beans, with no additional energy input required. Fourier transform infrared spectroscopy (FTIR) analysis confirmed better retention of aromatic compounds, particularly the C-H, C=O, and C-O bands. This indicates low oxidative degradation and preservation of complex aromas. The system also resulted in a significant reduction in energy consumption and CO_2 emissions while eliminating the need for fossil fuels or wood, thus aligning with a circular economic approach. Looking ahead, the development of a CFD (computational fluid dynamics) model is planned to optimize temperature control and steam flow dynamics.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Triboi, A. (2024) Impact of Coffee Roasting on Its Bioactive Properties. *Technical Scientific Conference of Undergraduate*, Chisinau, Vol. 2, 1223-1226. http://repository.utm.md/handle/5014/28061

[2] Endeshaw, H. and Belay, A. (2020) Optimization of the Roasting Conditions to Lower Acrylamide Content and Improve the Nutrient Composition and Antioxidant Properties of *Coffea arabica*. *PLOS ONE*, **15**, e0237265. https://doi.org/10.1371/journal.pone.0237265

[3] Gökmen, L. and Ferdous, H.I. (2021) The Effect of Roasting on Total Polyphenols and Antioxidant Activity of Arabica and Robusta Coffee. Master's Thesis, Mohamed El Bachir El Ibrahimi University-B.B.A.

[4] Sruthi, N.U., Premjit, Y., Pandiselvam, R., Kothakota, A. and Ramesh, S.V. (2021) An Overview of Conventional and Emerging Techniques of Roasting: Effect on Food Bioactive Signatures: A Review. *Food Chemistry*, **348**, Article ID: 129088. https://doi.org/10.1016/j.foodchem.2021.129088

[5] Ozel, M.Z., Yanık, D.K., Gogus, F., Hamilton, J.F. and Lewis, A.C. (2014) Effect of Roasting Method and Oil Reduction on Volatiles of Roasted *Pistacia terebinthus* Using Direct Thermal Desorption-GCxGC-TOF/MS. *LWT—Food Science and Technology*, **59**, 283-288. https://doi.org/10.1016/j.lwt.2014.05.004

[6] Lee, S., Choi, E. and Lee, K. (2024) Kinetic Modelling of Maillard Reaction Products and Protein Content during Roasting of Coffee Beans. *LWT*, **211**, Article ID: 116950. https://doi.org/10.1016/j.lwt.2024.116950

[7] Duangjai, A., Rawangkan, A., Siriphap, A., Kiddee, A., Yosboonruang, N. and Yosboonruang, A. (2024) A Promising Functional Food for Diabetes Prevention, Antioxidation, and Anti-Inflammation of Green Coffee Bean Extract. *Journal of Human, Earth, and Future*, **5**, 100-110. https://doi.org/10.28991/hef-2024-05-01-08

[8] Fellows, P.G. (2000) Food Processing Technology: Principles and Practice. 4th Edition, Woodhead Publishing, Chapter 16.

[9] Kaur, R., Kaur, M. and Gill, B.S. (2017) Phenolic Acid Composition of Flaxseed Cultivars by Ultra-Performance Liquid Chromatography (UPLC) and Their Antioxidant Activities: Effect of Sand Roasting and Microwave Heating. *Journal of Food Processing*

and Preservation, **41**, e13181. https://doi.org/10.1111/jfpp.13181

[10] Swarnakar, A.K., Srivastav, P.P. and Das, S.K. (2019) Optimization of Preconditioning Process of Pressure Parboiled Brown Rice (Unpolished) for Microwave Puffing and Its Comparison with Hot Sand Bed Puffing. *Journal of Food Process Engineering*, **42**, e13007. https://doi.org/10.1111/jfpe.13007

[11] Chikelu, C.C., Onyekwere, D.C., Ekwereike, A.C. and Okpanachi, A.I.P. (2015) Design of a Groundnut Kernel Roastmaster, a Review. *International Research Journal of Engineering and Technology*, **2**, 18-24.

[12] Santoso, A., Slameto, S., Savitri, D.A., Kusbianto, D.E. and Suud, H.M. (2024) The Effect of Using Fast Roast and Slow Roast Roasting Techniques on the Chemical and Organoleptic Characteristics of Robusta Coffee Beans (*Coffea robusta* L.). *International Journal on Food, Agriculture and Natural Resources*, **5**, 95-99. https://doi.org/10.46676/ij-fanres.v5i1.261

[13] Freitas, V.V., Borges, L.L.R., Castro, G.A.D., Almeida, L.F., Crepalde, L.T., Kobi, H.d.B., *et al.* (2024) Influence of Roasting Levels on Chemical Composition and Sensory Quality of Arabica and Robusta Coffee: A Comparative Study. *Food Bioscience*, **59**, Article ID: 104171. https://doi.org/10.1016/j.fbio.2024.104171

[14] Al-Shemmeri, M., Fryer, P., Farr, R. and Lopez-Quiroga, E. (2024) Development of Coffee Bean Porosity and Thermophysical Properties during Roasting. *Journal of Food Engineering*, **378**, Article ID: 112096. https://doi.org/10.1016/j.jfoodeng.2024.112096

[15] Suleman, R., Hui, T., Wang, Z., Liu, H. and Zhang, D. (2019) Comparative Analysis of Charcoal Grilling, Infrared Grilling and Superheated Steam Roasting on the Colour, Textural Quality and Heterocyclic Aromatic Amines of Lamb Patties. *International Journal of Food Science & Technology*, **55**, 1057-1068. https://doi.org/10.1111/ijfs.14388

[16] Zzaman, W., Bhat, R., Yang, T.A. and Easa, A.M. (2017) Influences of Superheated Steam Roasting on Changes in Sugar, Amino Acid and Flavour Active Components of Cocoa Bean (*Theobroma cacao*). *Journal of the Science of Food and Agriculture*, **97**, 4429-4437. https://doi.org/10.1002/jsfa.8302

[17] Tuncel, N.B., Uygur, A. and Karagül Yüceer, Y. (2017) The Effects of Infrared Roasting on HCN Content, Chemical Composition and Storage Stability of Flaxseed and Flaxseed Oil: A Review. *Journal of the American Oil Chemists' Society*, **94**, 877-884. https://doi.org/10.1007/s11746-017-2982-2

[18] Bagheri, H., Kashaninejad, M., Ziaiifar, A.M. and Aalami, M. (2019) Textural, Color and Sensory Attributes of Peanut Kernels as Affected by Infrared Roasting Method. *Information Processing in Agriculture*, **6**, 255-264. https://doi.org/10.1016/j.inpa.2018.11.001

[19] Idrus, N.F.M., Zzaman, W., Yang, T.A., Easa, A.M., Sharifudin, M.S., Noorakmar, B.W., *et al.* (2017) Effect of Superheated-Steam Roasting on Physicochemical Properties of Peanut (*Arachis hypogea*) Oil. *Food Science and Biotechnology*, **26**, 911-920. https://doi.org/10.1007/s10068-017-0132-0

[20] Kumoro, A.C., Wardhani, D.H., Kusworo, T.D., Djaeni, M., Ping, T.C. and Alhanif, M. (2024) A Brief Overview of Spray Drying Technology and Its Potential in Food Applications. *Journal of Human, Earth, and Future*, **5**, 279-305. https://doi.org/10.28991/hef-2024-05-02-09

[21] Kama, M., Thiam, A., Faye, K. and Ndiaye, B. (2025) Effect of Roasting Temperature and Duration on the Physico-Chemical and Sensory Properties of the Coffee-Guinea Pepper Roasted Blend. *African Journal of Food, Agriculture, Nutrition and Development*, **25**, 25466-25481. https://doi.org/10.18697/ajfand.138.24965

[22] Lombardi, L., Mendecka, B. and Fabrizi, S. (2020) Solar Integrated Anaerobic Digester: Energy Savings and Economics: A Review. *Energies*, **13**, Article 4292. https://doi.org/10.3390/en13174292

[23] Farinet, J.L. (1989) Energy Recovery from Agricultural By-Products in the Senegal River Delta: Biogas/Compost Sector. Career Thesis, Institute of Tropical Agronomic Research (IRAT) and Food Crops, Department of the French Agricultural Research Centre for International Development (CIRAD). https://agritrop.cirad.fr/605694/1/ID605694.pdf

[24] Benaissa, K. (2019) Energy Recovery from Household Waste, Camel Dung, and Urban Wastewater through Biogas and Natural Biofertilizer Production: Design and Construction of a 15 m^3 Pilot Biodigester in Tamanrasset (Southern Algeria). Ph.D. Thesis, University of Tamanghasset. https://www.researchgate.net/publication/332401505_Valorisation_energetique_des_dechets_menagers_crottins_de_dromadaire_et_eaux_usees_urbaines_via_la_production_du_biogaz_et_du_biofertiliseur_naturel_conception_et_construction_d'un_biodigesteur_pilote

[25] Aboubakar, Boli, Z. and Mbofung, C.M.F. (2016) Study of the Biogas Potential of Animal Waste: Cattle Dung and Poultry Droppings from a Zootechnical Center in Maroua—Cameroon. *Energies Renouvelables*, **19**, 447-464.

[26] Igoud, S., Tou, I., Kehal, S., Mansouri, N. and Touzi, A. (2002) Première Approche de la Caractérisation du Biogaz Produit à Partir des Déjections Bovines. *Journal of Renewable Energies*, **5**, 123-128. https://doi.org/10.54966/jreen.v5i2.891

[27] Camarena-Martinez, R., Lizarraga-Morales, R.A. and Baeza-Serrato, R. (2021) Classification of Geomembranes as Raw Material for Defects Reduction in the Manufacture of Biodigesters Using an Artificial Neuronal Network. *Energies*, **14**, Article 7345. https://doi.org/10.3390/en14217345

[28] Nzihou, A. (2020) Handbook on Characterization of Biomass, Biowaste and Related By-Products. Springer Cham Publisher, 1387. https://doi.org/10.1007/978-3-030-35020-8

[29] Mudhoo, A., Forster-Carneiro, T. and Sánchez, A. (2010) Biohydrogen Production and Bioprocess Enhancement: A Review. *Critical Reviews in Biotechnology*, **31**, 250-263. https://doi.org/10.3109/07388551.2010.525497

[30] Bottazzi, D., Farina, S., Milani, M. and Montorsi, L. (2012) A Numerical Approach for the Analysis of the Coffee Roasting Process. *Journal of Food Engineering*, **112**, 243-252. https://doi.org/10.1016/j.jfoodeng.2012.04.009

[31] Rahman, K.M., Melville, L., Fulford, D. and Huq, S.I. (2017) Green-House Gas Mitigation Capacity of a Small Scale Rural Biogas Plant Calculations for Bangladesh through a General Life Cycle Assessment. *Waste Management & Research*: *The Journal for a Sustainable Circular Economy*, **35**, 1023-1033. https://doi.org/10.1177/0734242x17721341

[32] Tsai, W., Lee, K. and Huang, C. (2025) Energy Efficiency and Carbon Emission Reduction in Coffee Roasting: Approach of Activity-Based Costing (ABC) Methodology. *Energies*, **18**, Article 1018. https://doi.org/10.3390/en18051018