Optimization of Far Infrared Radiation Power for Roasting Coffee

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Abstract

Investigating the possibility of using a Far Infrared heater to radiate heat sources for roasting coffee, this study measured the roasting temperature, roasting time, and color variation of a 1-kilogram coffee bean in a horizontal roaster coffee machine using different power heaters (1000, 1500, 2000, 2500, and 3000 W FIR). Comparing the results with consumer-acceptable roasted coffee colors (37.05 to 4.69 L*, 2.29 to 4.15 a*, and 2.70 to 6.29 b*)[1], it was observed that the coffee temperature roasted above 250°C with a moisture content of 9% (dry basis-db.). The findings demonstrated that as the FIR power increased, the coffee bean's temperature increased while the roasting time decreased. Moreover, the color attributes (CIE L*, a*, and b* values) decreased significantly with higher roasting temperatures and shorter times. The specific energy requirement varied at different FIR powers, with the minimum being 3750 J/g at 2500 W and the maximum at 6075 J/g at 1000 W, which could be attributed to the increased FIR power and sample surface temperature. This decrease in specific energy requirement was associated with reduced drying time. The respective roasting times for the FIR power heaters were as follows: 81 minutes for 1000 W, 40 minutes for 1500 W, 28 minutes for 2000 W, 20 minutes for 2500 W, and 18 minutes for 3000 W. These results indicate the potential of using Far Infrared heaters for efficient coffee roasting, offering control over temperature and roasting time to achieve desired color attributes and flavor profiles.

Keywords:

Far Infrared; Radiation; Coffee Bean; Color; Roasting

1. Introduction

Coffee, a beloved and popular beverage, is enjoyed by millions of people worldwide. It originates from the seeds of the Coffea plant, native to tropical regions. The journey of coffee beans from the farm to our cups involves several intricate processes, including harvesting, processing, roasting, and brewing. These steps contribute to the diverse array of flavors, aromas, and characteristics that make coffee so captivating. Vital in this transformation is the roasting stage, where green coffee beans turn into the aromatic, flavorful brown beans cherished by all. Through roasting, the distinct attributes of each bean are brought forth, resulting in a spectrum of tastes ranging from light and bright to dark and rich. These flavors are influenced by factors such as origin, species, and processing methods employed.

Throughout the roasting process, numerous chemical reactions and significant physical changes take place, making it a highly complex procedure. These transformations rely on the temperature-time profiles utilized during roasting [2]. Roasting is a heating method that releases both bound and free moisture from the food sample. Coffee is roasted using various techniques such as conduction (traditional drum roasters), convection (fluid bed roasters utilizing air as the heating medium), and radiation (infrared roasters). Convection roasting, a common method for coffee beans, exposes the unroasted beans to hot air at a temperature ranging from 200 to 230 °C for 12 to 20 minutes [3]. Roasters often utilize all three types of heat transfer, but their relative contributions to the overall heat transfer may vary significantly. Although infrared roasting has been reported, it remains an unusual method for coffee. In industrial practice, coffee is exclusively hot air roasted, making it sensible to distinguish between systems with prevailing conductive heat transfer and systems with prevailing convective heat transfer [4]. The first step in the roasting process involves the heating and expansion of unroasted beans, which alters their appearance and flavors. Roasts in the coffee industry are commonly categorized using the Agtron scale. However, terms like cinnamon, ordinary brown, French espresso, and more are also frequently used. Another index frequently employed by coffee producers is the CIE L*, a*, b* value, and hue angle colorimeter approach. The roasting level of coffee is determined by the CIE L* lightness value; a lower lightness value indicates a darker-roasted coffee hue [5].

Infrareds are electromagnetic radiations that are spectrally and directionally dependent, with wavelengths ranging between 0.78 and 1,000 µm. In the industry, two common types of IR heaters are electric heaters and gas-fired heaters. Gas-fired infrared heaters achieve combustion on the burner surface by igniting a premixed air and fuel stream. On the other hand, an electric heater emits radiation by passing an electric current through a resistance, increasing its temperature. Infrared radiation can be classified into three categories based on the temperature of the source: near-infrared (NIR), mid-infrared (MID), and far-infrared (FIR). The energy emitted by an emitter encompasses a variety of wavelengths, and the proportion of radiation in each band depends on various factors, including the emitter's temperature and emissivity. As a result, the spectrum dependency of IR heating needs to be taken into consideration [6]. FIR is in the wavelength range of 3 – 1000 µm and can be applied for different heating treatments such as baking, drying, roasting, thawing, and pasteurization [7]. The heat source's infrared radiation radiates to the heated surface and directly penetrates the material's inner layer. The molecules in the material's various layers absorb infrared radiation, which raises their vibrational energy level and causes it to fluctuate, producing heat and raising the temperature. This is one of the most significant benefits of infrared radiation since it stops energy losses and significantly preserves the product's original quality. The surface temperature rises rapidly, which is significantly faster than conduction and convection heat transfer because infrared radiation's energy is immediately absorbed by material molecules and has a very high energy density [8]. As a substitute roasting technique for beans and nuts, infrared roasting has grown in favor. Using infrared roasting has a number of benefits over conventional convective roasting techniques. The benefits of this approach are short roasting times, great heat efficiency, high diffusion coefficient, and small equipment [9].

In this investigation, FIR heaters were used as the heat source for roasting coffee. The effects of operating variables such as FIR power, roasting temperature, and roasting time on the physical properties of the roasted coffee beans were examined. Specifically, we focused on the changes in the color of the coffee beans during the roasting process.

2. Material and Methods

2.1. Sample preparation

Arabica green coffee beans weighing 1 kilogram underwent a wash process. The moisture content of the green coffee beans was 9% (wb), and they were roasted in a horizontal drum roaster.

2.2. Experimental setup

Fig. 1 shows the schematic diagram of the coffee beans roasting setup with the FIR heater. An electric FIR lamp with a power of 750 W was used to generate FIR, positioned in the middle of the drum. The coffee beans were exposed to FIR radiation by placing the sample under the FIR heater.

Roasting was conducted in a roasting chamber equipped with a controller to adjust the air temperature and drum speed. K-type thermocouples were utilized to measure and record the temperature of coffee beans exposed to different heater powers every minute. These thermocouples were connected to a data logger, the Graphtec GL840, with an accuracy of ±1.55°C, capable of handling various measurements from voltage, temperature, humidity, logic, and pulse signals.

The power analyzer used was the PROVA 6830A, capable of analyzing the power consumption up to the maximum demand of the heater. The heater power was connected to this power analyzer for the purpose of measurement and analysis.

The roasting process involved placing coffee beans under the FIR heater, using power settings of 1000, 1500, 2000, 2500, and 3000 W. The color change of the coffee beans was assessed using the CIE lab scale. The L*, a*, and b* values of factory-roasted coffee samples served as the standard for roasted coffee color and were compared with the color of FIR-roasted coffee.

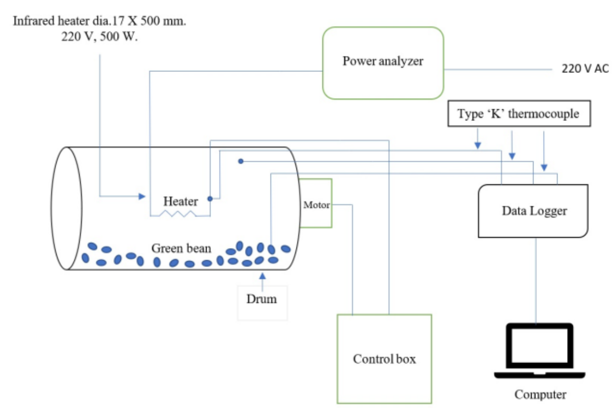


Fig. 1 Diagram of the FIR heater on coffee beans roasting setup.

2.3. Color analysis

Assessing the degree of roasting and determining the quality of the final coffee product heavily relies on color development, making it one of the crucial parameters to consider [10]. To measure the color of the coffee bean, a flat scanner system (jpeg format) with a resolution of 600 dips (dots per inch) was employed. The measured color is represented in three dimensions using the CIE lab system, denoted as L*, a*, and b* values, which provide specific color information about the coffee bean. The L* value represents the light-dark spectrum, ranging from 0 (black) to 100 (white). On the other hand, the a* value corresponds to the green-red spectrum, with a range from −60 (green) to +60 (red). Lastly, the b* value pertains to the blue-yellow spectrum, with a range from −60 (blue) to +60 (yellow) [11]. By analyzing these color values, valuable insights can be gained regarding the roasting process and the resulting characteristics of the coffee bean.

2.4. Specific energy consumption

During each roasting phase, the Power Analyzer was employed to measure the energy consumption. The device offers the flexibility of using test cables to directly measure current and power, or clamps for indirect measurements. Additionally, the tool comes with software to analyze the results and transfer data to a computer. To determine the energy consumed in roasting one kilogram of coffee beans, Eq. (1) is utilized for the calculation.

$$E_{kg} = \frac{E_t}{W_0} \tag{1}$$

Where E_{kg} is the specific energy required; E_t total energy consumed, J, and W_0 is the initial weight of the sample, g.

3. Result and Discussion

3.1. Temperature of coffee bean

Fig. 2 shows the variation in coffee bean temperature when exposed to different FIR heaters at 1000, 1500, 2000, 2500, and 3000 W power. As FIR power increased, the temperature of the coffee bean rose, and the roasting time decreased. However, it was observed that FIR powers of 1000, 1500, and 2000 W were insufficient to reach a temperature of 250°C within the standard 20-minute coffee roasting period. Prolonged roasting beyond the optimal time might result in a loss of flavor. For the optimal roasting temperature and time, FIR powers of 2500 and 3000 W proved appropriate, as they achieved a temperature increase of 250°C within 20 minutes, ensuring efficient coffee roasting.

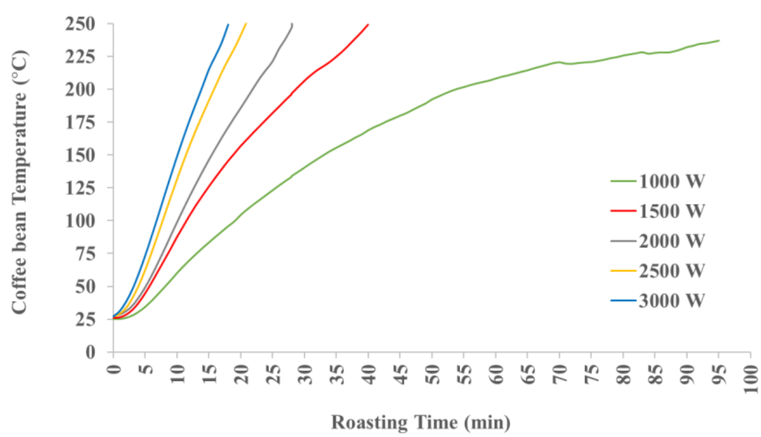


Fig. 2 Temperature and roasting duration of coffee beans at various FIR intensities.

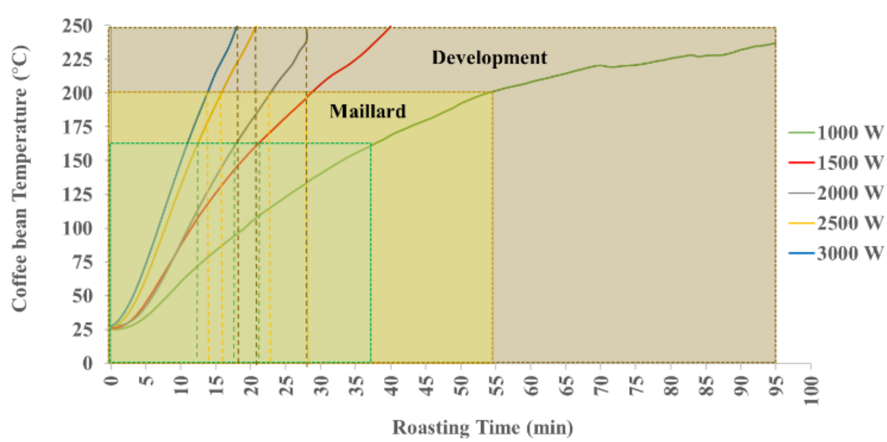


Fig. 3 Temperature profile of roasted coffee under different FIR power.

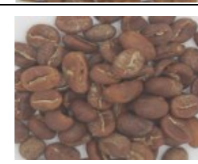
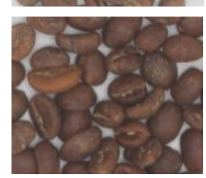
The roasting profile of coffee beans is shown in Fig. 3 as temperature rises steadily to a determined temperature of 250°C. At the beginning of the roasting process, the temperature and roasting time indicates the reaction of the drying phase, maillard, and development in coffee. The drying phase is the process of evaporation of water content in coffee that the color changes from green to yellow, temperature at 160°C. Maillard is permitted to produce melanoidin that has the aroma of entirely caramelized or browned sugar and color change also the same dark brown. It is also indicated that 1^{st} crack is 204 – 210°C spend at least 5 minutes. Development is the reaction becomes so energetic that it causes the breaking down of the cell walls. The second crack can be so energetic that pieces of the bean are blown off. Coffee roasted past the second crack is usually considered burnt when ending the roast will produce the flavors. At the end of roasting at FIR power 1000, 1500, 2000, 2500, and 3000 W for 81, 40, 28, 20, and 18 minutes, the color change to dark brown and oily in coffee beans that different flavor and aroma.

3.2. Color analysis

Color serves as a vital quality indicator in the roasting process, typically used to gauge the degree of roast. Table 1 illustrates the changes in the CIE L*, a*, and b* values of roasted coffee at different FIR powers over a duration of 0 to 81 minutes. A decrease in the L* value indicates that the color of the roasted coffee darkens with increasing temperature and roasting time, resulting in a blackish-brown appearance. This transformation is due to the occurrence of the Maillard reaction during the coffee bean roasting process. The a-value of roasted coffee diminishes at varying FIR powers, signaling an increased rate of brown pigment formation through the Maillard reaction. Similarly, the b-value of roasted coffee gradually decreases with longer roasting times, attributed to the thermal oxidation of polyphenols and the formation of Maillard products. The Maillard reaction significantly contributes to the development of aromatic compounds, leading to the production of brown material and color changes during roasting. The transition from green to cinnamon brown and eventually black with oily surfaces is a result of these reactions. As the roasting temperature and time increase, color attributes such as CIE L*, a*, and b* values exhibit a significant decrease, while moisture content experiences a slight decrease. Consequently, the color of the coffee beans undergoes changes due to the varied roasting temperatures and FIR power. When both temperature and FIR power rise, the lightness of the coffee color (L*, a*, b* values) decreases.

Table 1 CIE L*, a* and b* value on different FIR power.

	FIR emitter (W)	**Time (min)**	**L***	**a***	**b***	
	1000	0	43.60	3.65	13.88	
	1500	0	43.60	3.65	13.88	
Green	2000	0	43.60	3.65	13.88	
	2500	0	43.60	3.65	13.88	
	3000	0	43.60	3.65	13.88	

	FIR emitter (W)	**Time (min)**	**L***	**a***	**b***	
Yellow	1000	32	42.91	3.61	12.72	
	1500	24	41.91	2.58	12.50	
	2000	19	41.26	2.12	10.29	
	2500	14	41.45	1.92	9.84	
	3000	11	40.40	2.18	8.96	
Brown	1000	50	33.20	2.91	4.54	
	1500	28	32.54	2.62	4.34	
	2000	27	29.98	1.97	2.59	
	2500	18	28.93	0.38	0.65	
	3000	14	29.35	1.32	1.73	

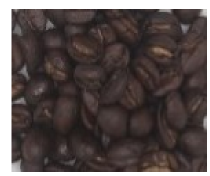
	FIR emitter (W)	Time (min)	L*	a*	b*	
Dark brown	1000	81	29.96	1.51	1.88	
	1500	40	29.41	1.72	1.94	
	2000	28	29.91	1.15	1.31	
	2500	20	28.8	0.27	0.59	
	3000	18	29.30	0.33	0.71	

Table 2 Color of roasted coffee with various times on CIE L*, a*, and b*value compared with the standard color (SCAA).

Type of coffee	Color			Degree of roasted	SCAA/Agtron scale [12]
	L*	a*	b*		
Reference coffee	28.47	7.09	11.50	Light	70
	23.96	5.72	7.93	Medium	58
	19.32	3.57	2.89	Dark	36
Roasted coffee	26.98	6.24	9.46	Light	66
	22.41	6.24	8.04	Medium	55
	16.44	3.08	2.83	Dark	33

Table 2. shows the color of roasted coffee according to the color of the reference coffee. There were 3 levels of reference coffee used: light roast, medium roast, and dark roast. In the coffee industry, in addition to using the SCAA/Agtron scale, the colorimeter CIE lab parameter is also used in coffee roast classification, especially the CIE L* lightness value, which was used to identify the roasting degree of coffee. The investigation into the color of coffee found that at the light, medium, and dark roast levels, the coffee brightness (L*) was in the range of 16.44 – 26.98, and the* color value was in the range of 3.08 – 6.24. and b* color value is in the range of 2.83 – 9.46, which corresponds to the color value of roasted coffee derived

from the reference coffee color and within the criteria acceptable to consumers. It can be seen that as the roast intensity increases, the CIE L*, a*, and value tends to decrease dramatically.

3.3. Specific energy consumption

Table 3 The amount required specific energy for roasting coffee by FIR heater.

FIR power (W)	Roasting time (min)	Specific Energy Consumption (J/g)
1000	81	6075
1500	40	4500
2000	28	4200
2500	20	3750
3000	18	4050

Table.3 shows the required specific energy for roasting coffee using an FIR heater. According to, the minimum specific energy requirement was 3750 J/g which occurred at FIR power 2500 W, while the maximum specific energy was 6075 J/g at FIR power 1000W. This is because with increasing FIR power and sample surface temperature increases. Therefore, roasting time is reduced and the required specific energy decreases. According to the table, although roasting with a 3000 W power heater takes 18 minutes, which is 2 minutes less than roasting with a 2500 W power heater, the required specific energy was 4050 J/g. Because it has a higher energy consumption while roasting time is similar.

4. Conclusion

The results of this study demonstrated the effective use of the FIR heater as a heat source for coffee roasting. The heater power of 2500 W proved to be suitable for roasting coffee within a 20-minute timeframe, resulting in coffee brightness that matched the color of roasted coffee obtained from the reference coffee color, meeting consumer acceptability criteria, and requiring a specific energy of 3750 J/g. To compare electricity consumption between roasting with an FIR heater and an electric heater, it was found that roasting with an electric heater at 1800 W consumed 0.24 kWh/kg of electricity for 90 minutes [13]. In contrast, roasting with an FIR heater at 2500 W used 0.83 kWh/kg of electricity for 20 minutes. Although using an electric heater for coffee roasting consumed less energy than using an FIR heater, the roasting process took up to 70 minutes.

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