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Optimization of Fluid-Type Roasting Machine on Robusta Roasted Coffee Characteristics

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Abstract. *Coffee is a superior plantation commodity playing an important role in Indonesian economic growth, as a contributor to income and provider of employment. The handling process of coffee, particularly at roasting stage, has a significant impact on the quality of the final product. The Research Center for Appropriate Technology, National Research and Innovation Agency, has developed fluid-type roasting machine with a capacity of 750 grams (g) and fueled by LPG (liquefied petroleum gas). Therefore, this research aimed to determine the characteristics of robusta roasted coffee through performance tests of fluid-type roasting machine. Performance tests were carried out to determine the static characteristics of temperature sensor and ensure accurate provision as well as consistent readings in effectively controlling roasting process. Some of the characteristics that were determined included moisture content by thermogravimetric method, color, texture, caffeine, and microscopic analysis. The results showed that fluid-type roasting machine had a high-temperature sensor accuracy of 1.3% and repeatability of 0.69. The physical and chemical analysis showed that roasting temperature significantly affected the characteristics of roasted coffee beans. Additionally, higher temperature caused an increase in cracking of coffee beans, ash content, texture, caffeine content, and darker color, along with lower moisture content.*
Keywords: *optimization; roasting; coffee; fluid-type; characterization.*

Type of the Paper: Regular Article.

1. Introduction

Coffee is a superior plantation commodity playing an important role in Indonesian economic growth, as a contributor to income and provider of employment [1]. This commodity is increasingly developing as a source of raw materials for the food and beverage industry [2]. However, the product quality of the final product is significantly determined by the handling process during harvesting, processing, and roasting [3]. Coffee harvesting is often observed from the level of fruit maturity to when the fruit is red. During the processing stage which is classified into primary and secondary, roasting is carried out on dried coffee beans rather than powder form [4]. In primary stage, coffee fruit is processed into dry beans, while secondary processing includes roasting, cooling, and grinding. Moreover, roasting is the final stage in preparing green beans for

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grinding, brewing, and consumption [5].

Roasting technology was originally carried out conventionally using a simple pan [6]. As technology developed, innovations occurred using manual and automatic machines. Based on previous investigations, two machines have been developed, namely cylinder-type and fluid-type. Cylinder-type principle heats beans with hot gas in a horizontal or vertical drum equipped with a stirrer and heat transfer by conduction [7,8]. Meanwhile, fluid-type keeps coffee beans in the air using a blower and roasts with convection heat transfer to increase the heating contact with the material. This machine helps avoid emptiness in beans, as there is no contact with the cylinder wall. However, the limitations of fluid-type roasting machine are wide application for large-scale coffee roasting and high consumption of electrical power [9]. The length of roasting time varies considerably depending on the system and type of machine. Generally, the time required for the process takes approximately 15-30 minutes to maintain the quality of coffee in terms of color and the desired flavor [10].

Roasted coffee with fluid-type roasting machine needs physical and chemical analysis. Roasting results can be divided into three levels, namely light, medium, and dark, which differ based on color, chemical content, and texture. Measurement of caffeine content in coffee can be analyzed using High-Performance Liquid Chromatography (HPLC) [11]. The commercial HPLC separates the components of coffee based on differential affinities of the analyte for stationary and mobile stage, followed by detection using UV detectors [12]. The pH of mobile stage is adjusted to achieve a critical ratio of ionic and nonionic components, thereby increasing the resolution between closely eluting compounds. The particle size of column packing, as well as the length and diameter, influence the separation, resolution, and other chromatographic conditions.

During sample preparation, the recovery of analytes using the extraction method can be further improved through a suitable internal standard [13]. Suitable solvents such as chloroform, dichloromethane, and ethyl acetate, are generally used for extracting caffeine from coffee beans based on recovery research. Additionally, chromatographic methods are frequently used along with spectroscopic commonly known as hyphenated. In this context, the complex from chromatographic methods enters the spectroscopic through the interphase process [14]. Based on the description, this research applies the concepts of HPLC method development using an internal standard to analyze caffeine content in different coffee beverages. The validation of the developed HPLC with optimized conditions obtained during the trial runs has been studied based on ICH Q2 (R1) guidelines [15].

According to the Research Center for Appropriate Technology, National Research and Innovation Agency (PRTTG BRIN), the development of fluid-type roasting machine has been carried out with a capacity of 750 grams (g) and fueled by LPG (liquefied petroleum gas).

Therefore, this research aimed to determine the characteristics of robusta roasted coffee through performance tests of fluid-type roasting machine that has been designed. Performance tests were conducted to determine the static characteristics of temperature sensor to ensure accurate provision and consistent readings in effectively controlling roasting process. The next stage is to conduct physical and chemical analysis of roasted coffee to obtain information about the characterization of good quality coffee products, meeting standards, and consumer preferences.

2. Materials and Methods

This research was conducted at PRTTG BRIN, Subang, in December 2023. The tools used were digital scales, thermometers, coffee beans grinders, containers, measuring cups, plastic, fans/coolers, gas cylinders, and roasting machine. The ingredients included coffee beans and gas for the grill. To support the optimization of roasting machine, moisture content analysis, color test, texture test, caffeine analysis, and microscopic analysis of roasting results are carried out. Subsequently, primary data were collected and the results of the operation of fluid-type roasting machine from coffee beans were inserted and roasted to obtain a desired level.

By varying temperature and time of roasting process, this research aimed to determine the characteristics of roasted coffee produced. The specifications of fluid-type roasting machine that has been designed were made of stainless steel with a size of 1.5 m x 1 m x 1.7 m, a capacity of 750 g/process fueled by LPG, and a gas consumption of 0.1 Kg/process. Roasting room temperature was equipped with type K thermocouple temperature sensor that could monitor and record data. Data processing uses Arduino Mega with software for programming Arduino IDE and fluid-type roasting machine is shown in Fig. 1.

Description:
1. Input materials
2. Roasting room
3. Temperature sensor
4. Burner chamber
5. Monitoring and temperatures record
6. Electrical box
7. Exhaust
8. Skin dump

Fig. 1. Temperature-monitored fluid-type roasting machine

Fig. 1 shows the parts of fluid-type roasting machine, namely 1) Material input funnel is used to enter coffee beans, 2) Roasting room, 3) Temperature sensor to determine temperature condition of roasting room, 4) The burner room contains a coal heater as roasting machine burner, 5) Monitoring and recording of roasting room temperature, 6) Electric panel for roasting machine, 7) Exhaust gas from roasting, and 8) Roasted coffee skin disposal container. Fowchart of roasting process is shown in Fig. 2.

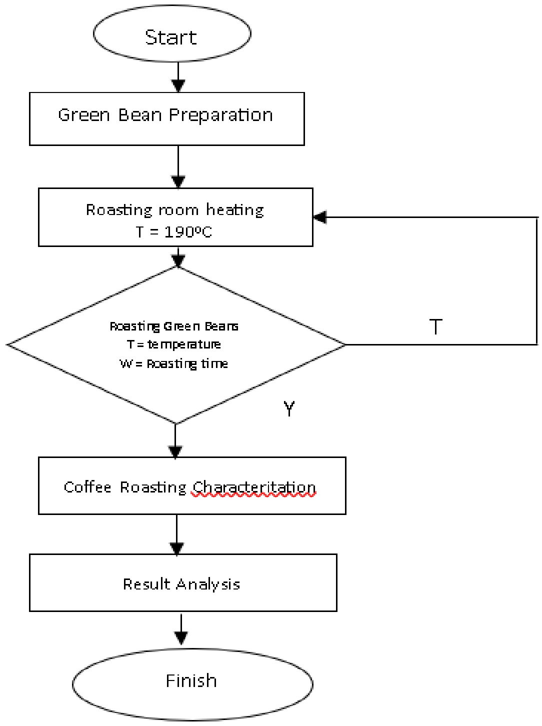

Fig. 2. Flowchart of roasting process

Based on flowchart in Fig. 2, the initial stage is to prepare coffee beans to be roasted, set roasting room temperature to 190^{0}C, and put coffee beans into roasting room. The length of time and temperature of roasting were taken in stages to determine when coffee beans experienced physical and chemical changes. To obtain a total of 8 samples, data collection starts from green (Light) to burnt (Dark) stage.

The sampling temperature ranged from 115^{0}C - 215^{0}C with a time of 5 minutes - 20 minutes. This was followed by the characterization of roasted coffee, which included moisture content, color test, texture, caffeine analysis, and microscopic object analysis. Color test data collection was carried out using Konica Minolta Chromameter CM-700d tool. Analysis of moisture content used SNI.01-2891-1992 method, texture analysis applied Texture Analyzer TA.XT Stable micro system. Meanwhile, caffeine analysis [16] used HPLC Agilent 1290 Infinity II and microscopic object analysis applied Keyence VHX7000 digital microscope. Coffee bean samples were of Robusta variety from Subang, West Java.

Moisture content analysis was carried out following SNI method 01.2891-1992 by weighing 2 g of samples and heating in an oven at 105^{0}C for 3 hours. Subsequently, the sample was put in the desiccator for 1 hour and weighed, with the process repeated in the oven for 1 hour to achieve a constant weight.

The color test was carried out using Konica Minolta CM700D tool. Initially, the sample was put into a cup of 10 g and Konica CM700D spectrophotometer was turned on and calibrated in black and white. The sample was directed to the chromameter using the target mask SAV. The test was conducted with 3 repetitions and set through an app on PC to obtain data regarding L*, a*, and b* values.

Texture testing was carried out using the Texture Analyzer tool. The microsystem XT Stable probe P36 will produce hardness values. The test was carried out at a speed of 2 mm/s, strain 50%, trigger force 2 g, break mode off, stop plot at the start position, and fare mode auto. The sample was placed under the probe and operated until cessation of operation to obtain the hardness value.

Caffeine analysis was carried out after coffee was brewed by extracting. Initially, a total of 5 g of samples were extracted by adding 100 ml of aquadest water, followed by heating for 30 minutes in a water bath and covering with aluminum foil. The samples were allowed to cool, added to approximately 500 ml of water, and strained using Whatman paper. Approximately 1 ml of filtrate results was collected in a 10 ml measuring flask and added with aquadest. Subsequently, the diluted filtrate was inserted into a 1.5 ml vial using a syringe and a 0.45 microfilter to impurities in the sample injected into the Agilent 1260 Infinity II HPLC. An analysis was performed and the results obtained were in a linear curve and area that appeared with the same run time. The wavelength used was 275 nm through Diode Array Detector (DAD). The analysis process used 60% methanol solvent and 40% water for chromatography. Solvent percentage determination was carried out on the Agilent 1260 Infinity II HPLC application operating system with a 10-minute stop run for each sample and performed 3 times.

The measurement of the diameter of roasted coffee with fluid-type roasting machine was carried out using Keyence VHX7000 digital microscope. A magnification of 20 x was able to measure the diameter of coffee beans that were randomly taken from 5 g samples with 3 repetitions.

3. Results and Discussion

3.1. Roasting Room Temperature

Temperature in coffee roasting room is one of the important factors affecting the quality of roasted coffee. This is because the right temperature will produce coffee with optimal flavor. Roasting at extremely low room temperature can cause coffee beans not to ripen completely, resulting in a sour and astringent taste. Meanwhile, burning occurs at extremely high temperature, leading to a bitter and sour taste [17].

In this research, roasting temperature was detected using temperature sensor in the form of type K thermocouple ranging from 0 to 400^{0}C [18]. The static characteristics of temperature sensor were tested by taking data 10 times. The analysis carried out included accuracy, repeatability, repetition, and precision.

3.2. Temperature Sensor Accuracy

Temperature sensor accuracy is the ability of the sensor to measure temperature precisely, which can be expressed in various methods, including the use of relative error [19]. The accuracy is obtained by comparing the reading results of type K thermocouple temperature sensor with a standard measuring instrument. The measurement was carried out using Universal data logger, type K thermocouple brand Daqpro S300 with a reading accuracy of ± 0.5 (°C), as shown in Table 1.

Table 1. Comparison of temperature sensor readings with standardized measuring instruments

Number	Sensor type K thermocouple	Universal data logger, type K thermocouple (Daqpro S300)	Error
1	19.2	19.8	0.6
2	20.5	20.8	0.3
3	21	21.4	0.4
4	23.2	23.7	0.5
5	28.5	28.7	0.2
6	33	33.3	0.3
7	32.1	32.2	0.1
8	31.6	31.7	0.1
9	29	29.6	0.6
10	30	30.3	0.3
Error Average			0.34
Standard Deviation			0.174356

Based on Table 1, the mean error of all measurements was 0.34°C. This showed that on average, data loggers tended to give slightly lower readings than type K thermocouple sensors of 0.34°C. The standard deviation of the error was 0.174°C, showing the distribution or variation of individual errors against the mean of errors. Based on the following formula, the average percentage of errors showed that the sensor readings had different values when compared to standard measuring instruments. The average value of the percentage errors in temperature measurement was 1.3%, showing that the measurement results were accurate and could be trusted. From the calculation of the mean, on average, the error between the sensor reading and the Daqpro data logger reading was approximately 1.3% of the sensor reading value.

$$\%\ error = \frac{error\ average}{cencor\ average}\ x\ 100\% \quad (1)$$

The research by Sumiarsih [20] was carried out to determine the rate of hydrogen gas production. During the experiment, hydrogen gas temperature monitoring system was made using LM35 sensors and type K thermocouple to determine temperature of hydrogen gas in the storage system. Type K thermocouple sensor produced a percentage error of 1.9% and LM35 sensor was 0.3%. In this research, the average sensor error was 0.34°C with a deviation of 0.17, showing the need for correction of the difference in value readings to improve accuracy. Correction to temperature measurement results was carried out by comparing the sensor measurement value with the actual temperature value. This process was performed using the linear regression method to determine the relationship between two variables, namely the sensor reading and the actual temperature value. Fig. 3 shows correlation results of temperature sensor readings with standard measuring instruments, namely Universal data logger, type K thermocouple.

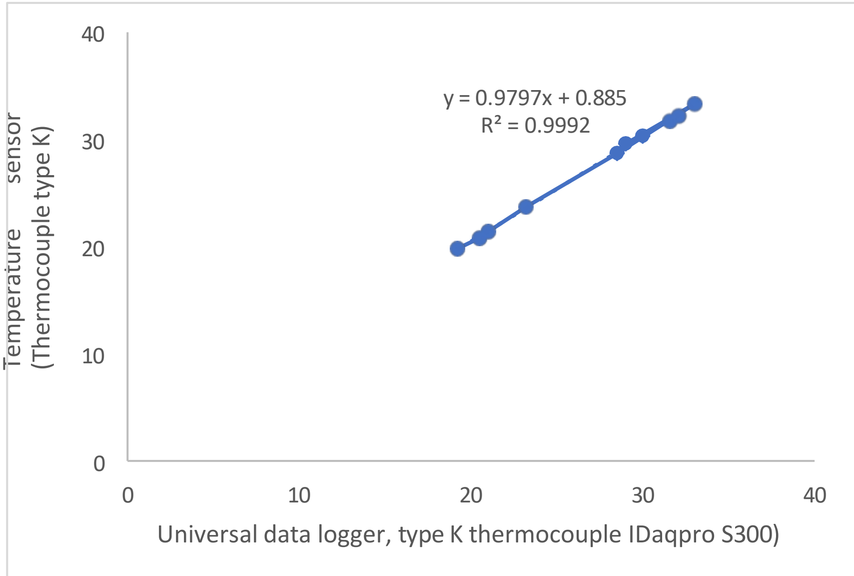

Fig. 3. Comparison of temperature sensor values with Universal data logger, type K thermocouple

Fig. 3 shows a significant difference in measurement readings between the sensor and the standard measuring instrument, which was compared to obtain the calibration correction equation. Based on the results, the correction equation 0.9797x + 0.885 could calibrate temperature sensor measurements with a value of $R^2 = 0.9992$, which showed a very high accuracy. Previous research [21] stated that the application of type K thermocouple with temperature range of -200°C to +1200°C, for autoclave temperature measurements, has a value of $R^2 = 0.9989$, showing very high accuracy.

Table 2. Type K thermocouple temperature sensor repeatability reading results to determine sensor precision level

No.	Temperature sensor readings
1	30.75
3	30.50
4	29.99
5	31.1
6	30.02
7	29.2
8	29.21
9	30.75
10	30.75
Average-Flat	29.904
Standard deviation	0.69

3.3. Repeatability of type K thermocouple temperature sensor

Data sampling was carried out 10 times and obtained every 2 minutes with data acquisition, as shown in Table 2.

Table 2 shows that the average value of sensor readings with 10 repetitions every 2 minutes is 29.9°C with a deviation value of 0.69. This data shows that the sensor has a high level of stability and precision indicated by a small deviation value.

Table 3. Effect of temperature on coffee beans cracking

No	Coffee beans picture	Coffee powder picture	Diameter coffee beans	Temperature roasting (^{0}C)	Color	Hardness coffee beans roasting	Caffeine Content (% in 0.3 g)
R1			8.38 mm	27	Light	53169.32	0.006463
R2			8.66 mm	115	Light Medium	9466.43	0.011485
R3			8.94 mm	128	Light Medium 2	7479.882	0.012575
R4			9.04 mm	151	Medium	6763.59	0.012456
R5			9.36 mm	158	Medium 2	677.036	0.013744
R6			10,6 mm	169	Light Dark	5897.798	0.014123
R7			12.17 mm	187	Medium Dark	2946.2	0.014331
R8			12.89 mm	215	Dark	1872.756	0.007511

3.4. Effect of roasting temperature on cracking in coffee beans

Roasting temperature has a close relationship with cracking in coffee beans. Cracking is the process of releasing carbon dioxide gas from coffee beans, which occurs when temperature of coffee beans reaches around 190-200°C. This carbon dioxide gas is trapped inside coffee beans during drying and released when there is an increase in temperature. At low roasting temperature, carbon dioxide gas will be released slowly, leading to relatively quiet and less violent cracking, thereby producing product with a mild and sour taste. At high temperature, carbon dioxide gas will be released quickly. This causes relatively loud and rumbling cracking to produce coffee with a darker and richer flavor [22].

In this research, the samples observed were coffee beans that were still green to burnt. Observations were made using Keyence VHX7000 digital microscope with 20 x magnification, and images of roasting temperature relationship to cracking were obtained, as shown in Table 3.

Table 3 shows that at the beginning, coffee beans had not been roasted at room temperature 27^{0}C with a seed hemisphere of 8.38 mm and green in color. As roasting temperature began to rise, the first cracking occurred at 158^{0}C characterized by a change in color to brown/medium and small cracks 9.36 mm wide on the surface. The form of cracking could provide information about the roast level of coffee beans. This is because roasting at the medium level would have relatively small not-too-deep cracks.

At 187^{0}C the second cracking occurred characterized by a larger crack of 12.17 mm and a deep black color. In this condition, dark roasted coffee beans had extensive and deeper cracks due to increasing temperature. Subsequently, measurement was conducted using type K thermocouple sensor with temperature ranging 0-2315ºC, accuracy of ± 0.2%, and precision of ± 0.1. Temperature plays an important role in determining the cracking level during roasting process due to the release of gases and moisture from coffee beans when heated. Based on observation, the first crack occurred at temperature of approximately 196°C, where coffee beans started to expand and make a small crack-like sound. The second crack occurred at temperature of approximately 227°C, where coffee beans expanded further and made a louder pop-like sound. With lower temperature, cracks occurred more slowly, producing a lighter coffee with more acidic and brighter taste. At higher temperature, cracks occurred faster, resulting in a darker coffee product with a more bitter and richer taste.

3.5. Effect of roasting temperature on caffeine

Based on Table 3, coffee beans sample R1 at room temperature 27^{0}C has the lowest caffeine content of 0.006463%. R8, which was roasted at 215^{0}C had the highest caffeine content of 0.007511%. Generally, caffeine is contained in the form of crystals scattered in coffee beans' cell [23]. Based on previous research [24], the lowest caffeine content of 1.01% was shown at 190°C while the highest value of 1.79% was at 210°C. For specialty coffee, roasting temperature was mostly selected in range between 160–200°C with time ranging from 4 to 12 minutes [25].

Roasting process significantly affects the chemical composition of coffee. The initial stage of the process is drying, where temperature is below 160°C, followed by roasting at 260°C. After reaching 190°C, pyrolytic reactions are triggered, causing oxidation, reduction, hydrolysis, polymerization, decarboxylation, and other chemical changes [26]. Moreover, time-temperature conditions define the color and the product quality [27].

3.6. Effect of roasting temperature on moisture and ash content

The process of roasting coffee beans will cause the evaporation of moisture content, as shown in Fig. 4.

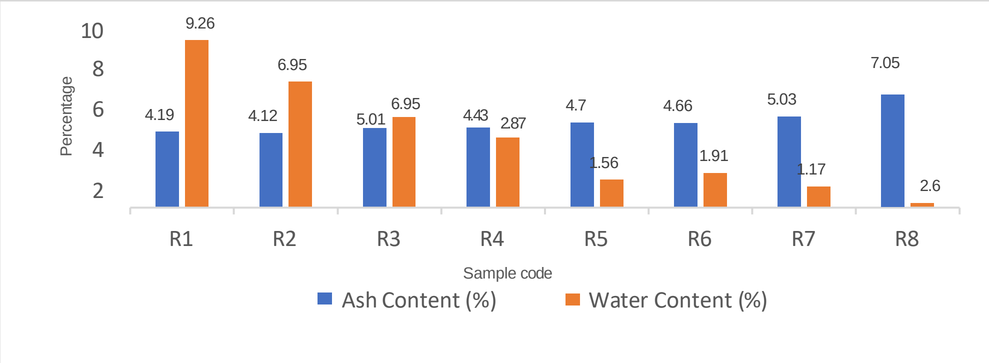

Fig. 4. Graph of the relationship between the percentage of moisture content and ash content against temperature roasting

According to Fig. 4, sample R1 which was not roasted had the highest moisture content of 9.26%. Sample R8 roasted at 215^{0}C had the lowest moisture content of 0.26%. This showed that higher roasting temperature corresponded to greater removal of moisture content. Referring to INS 8964:2021, the ideal roasted coffee moisture content is approximately 3-4%. Moisture content higher than 4% can cause coffee to spoil easily, with a value below 3% leading to brittleness and breaking. In this research, samples R2, R3, R4, R5, and R6 had ideal moisture content, while R1 and R8 had extremely high or low values.

The relationship between roasting temperature, moisture content, and ash content of roasted coffee beans is complex. However, higher roasting temperature will lead to a decrease in the moisture content and increased ash content of roasted coffee beans. Based on Fig. 4, sample R8 had the highest ash content of 7.05%, while R2, R3, R4, R5, and R6 had ideal ash content of approximately 4-5%. Sample R7 had a slightly lower-than-ideal ash content of 4.7%. Sample R1 has the lowest ash content of 4.19%. This showed that the samples had ash content that was still within a reasonable range. Samples R1 and R8 have ash content that is slightly higher or lower than ideal, but not extremely significant. According to INS 8964:2021 regarding Roasted and Ground Coffee, the allowable ash content is 4%-6%. The value extremely high (>6%) can cause coffee flavor to be bitter and unpleasant. Meanwhile, extremely low value (<4%) can lead to a lack of richness and complexity.

The average moisture content of green coffee beans was 12.5% (measured in 100 samples) and decreased with roasting time, reaching a minimum of 0.72% in 12 minutes at 275°C. Dutra et al. [28] Aliah et al. [29]. Franca et al. [30] Aliah et al. [29] found the average of 9 g/100 g moisture content in green coffee samples, which was in the range reported in the literature by Clarke [31]; 8.5-13 g/100 g). This value further decreased to an average of 1.5 g/100 g after roasting.

3.7. Effect of roasting temperature on color and texture

Table 3 shows that the highest hardness value is in green coffee beans, which is 53169.319 N. Meanwhile, the lowest hardness value of roasted coffee is 677.036 N. This occurs because R5 sample has the lowest hardness level, making coffee to be easily crumbled and broken. In this position, cracking occurs by releasing carbon dioxide from coffee beans. Directly proportional to the texture, the color of coffee beans also affects the level of hardness, including roasting temperature. This is because higher roasting temperature increases the crunchiness of the roasted coffee.

The texture of R8 has the highest roasting temperature level of 215^{0}C. This causes coffee to burn quickly and have a deep black color, with hardness value of 1872.756 N. Coffee R8 is different from R5 with temperature of 158^{0}C, which has experienced maximum evaporation, leading to the occurrence of lower hardness and cracking. R6 roasted at 169^{0}C experienced cracking as evidenced by the diameter of the crack until 10.6 and hardness increased back to 5897.798. The increase occurred because the cracked coffee reabsorbed the surrounding air, thereby increasing hardness. High temperatures will cause coffee to crack quickly, absorb the surrounding air, and return to crumb. Therefore, there is a need for precipitation before being analyzed at least 3 days after roasting [32].

Color analysis is divided into 2, namely coffee beans that have been roasted and powder form. This is to increase the homogeneity of coffee color for the sample tested to remain the same. The initial color of coffee is green but changes after roasting from brown to black.

Coffee is measured using Konica Minolta Chromameter CM700d tool by measuring L*, a*, and b* values. L* value shows the color of the sample between white to black, a* shows red to green, and b* shows from yellow to blue. The higher the L* value, the brighter/whiter the color shown by the sample. This serves as the basis that coffee color testing takes L data to determine the level of light-to-dark color density. Therefore, with a longer and higher roasting temperature, the faster coffee becomes black. For a large a* value, coffee appears more green, larger b* value shows more blue. When the a* and b* values are smaller, the sample will be more dark. The color change occurs due to the process Maillard reaction and variations in the structure of proteins and polysaccharides in coffee beans [33]. The main chemical reactions during roasting are the Maillard and Strecker degradation. The non-volatile compounds included in the Maillard reaction are amino acids and reducing sugars that form the end product melanoidin during roasting [34].

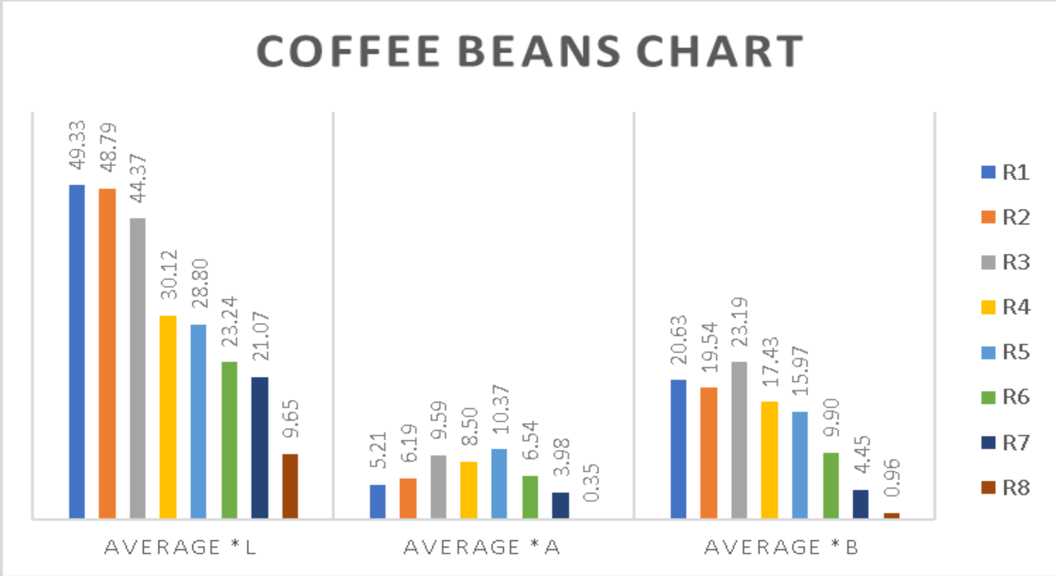

Fig. 5. Color test graph of coffee beans (*green beans coffee*)

Based on the graph Fig. 5, R1 has L value of 49.39, a 5.19, and b 20.60. The powder form presented in Fig. 6 has L value of 50.44, a 4.30, and b 23.08, showing that coffee beans still have a light color. Meanwhile, light-medium coffee has a lower color, namely L 30.18, a 7.77, and b 17.45 for beans, as well as L 34.66, a 10.91, and b 24.78 for powder form. Coffee beans that have experienced discoloration occur due to the heating process. R6 coffee has a medium color with a value of L 23.27, a 6.53, and b 9.87 for beans, as well as L 14.33, a 7.85, and b 11.98 for powder. Dark coffee beans with a value of L 9.65, a 0.32, and b 0.94 and dark coffee powder with L 6.94, a 0.49, and b 1.06, show optimal level of heating and a significant change from color to solid black.

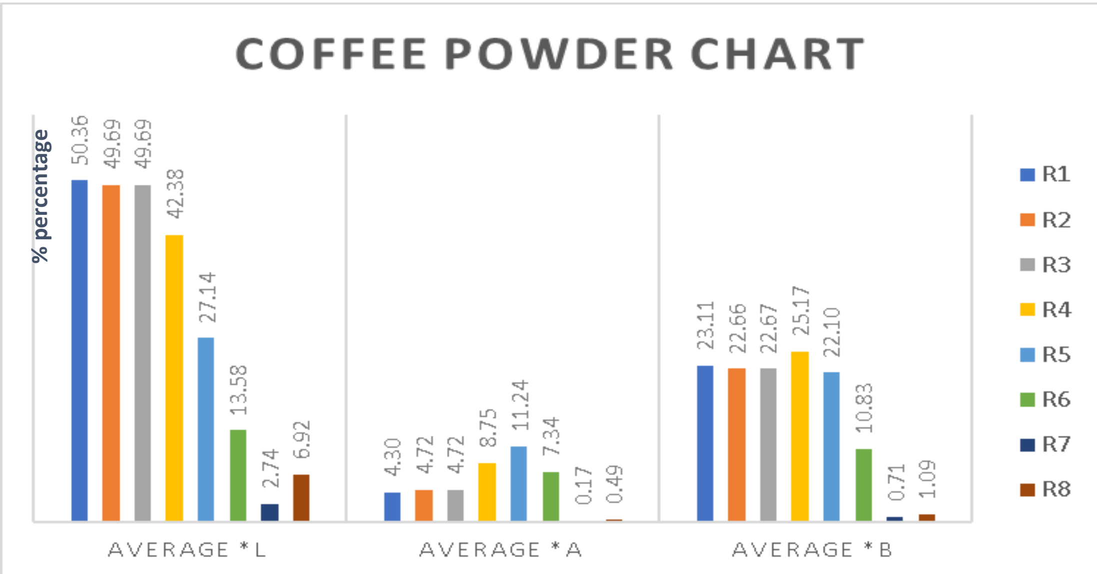

Fig. 6. Graph of coffee powder

Color changes occur because the water and ingredients contained in coffee beans are evaporated, resulting in drying from green to brown and black or burnt. The color of coffee for consumption is preferred in the medium form, because extreme green produces sour and astringent taste, while black coffee has high tendency to burn and bitter. In evaluating the level of coffee roasting, most companies still rely on highly experienced roasting masters, but only observe sensory aspects such as color and aroma [35]. The results of graphs 5 and 6 show that the samples experienced color changes marked by varying values of L*, a*, and b*.

4. Conclusions

In conclusion, this research showed that fluid-type roasting machine had a high-temperature sensor accuracy of 1.3%. Roasting temperature had a significant influence on cracking, moisture and ash content, color, texture, and caffeine content of roasted coffee beans. The results also showed that higher roasting temperature correlated with greater cracking, lower moisture content, elevated ash content, darker color, harder texture, and increased caffeine content of roasted coffee beans. The final product obtained had moisture, ash, color, texture, and caffeine content following SNI 8964: 2021 standards. These results served as a foundation for the development of better and more efficient coffee roasting technology in the future.

Abbreviations

Not applicable.

Data availability statement

Data will be shared upon request by the readers.

CRediT authorship contribution statement

Ari Rahayuningtyas: Conceptualization, Methodology, Resources, Formal analysis, Investigation, Data curation, Funding acquisition, Writing – review & editing. Ida Farikha Azizah: Writing – original draft, Validation, Data curation, Formal analysis, Conceptualization. Dadang Dayat Hidayat: Conceptualization, Supervision, Project administration, Data curation, Writing – original draft. Yusep Ikrawan: Resources, Formal analysis, Investigation, Funding acquisition, Writing – review & editing. Steven Witman: Data curation, Formal analysis. Alifia Fauziah Rohzan : laboratory data analysis

Declaration of Competing Interest

The authors of this manuscript declare no conflict of interest or competing interest.

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