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Roasted coffee beans characterization through optoelectronic color sensing

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ABSTRACT

The degree of roasting of the coffee determines the physical properties of the bean which are directly represented in the quality of the coffee, to classify the coffee bean efficiently represents a challenge that has been addressed from different technological approaches with colorimeters. This research aims to simplify the identification of the roast level of ground coffee on the Agtron scale by characterizing the degree of roast using an optoelectronic color sensor and establishing a correlation between the Red, Green, and Blue (RGB) scales. This allows for the assurance of quality levels of the beans right from the roasting process. This research comprehends the collection and preparation of samples, the definition of RGB and CIE L*a*b* values, and their interpretation in the Agtron scale using the red component of the RGB scale. The results showed an efficient and accurate estimation for the roast degree of ground coffee beans (0.1371 MSE) that uses minimum processing requirements and a function to assess the intermediate values in the Agtron scale. The characterization of the roast degree of ground coffee beans using data collected from an optoelectronic color sensor through a high-precision function with a linear structure enables the description of intermediate values not fully represented on the Agtron scale. This enhances the process of identifying the roast degree, facilitating subsequent quality assurance processes by maintaining the beans at the desired roast level.

Key words: Agtron; coffee bean color; color sensor; RGB.

1 INTRODUCTION

Coffee is the second most valuable basic product in the world only after petrol oil: there are more than 20 million producers in 50 countries and over 11 million hectares dedicated to its cropping. Coffee industry fostered social and economic change due to its drive to the complementary industry (Federación Nacional de Cafeteros de Colombia, 2023; Pérez Toro, 2013) and manual classification of the coffee bean (that takes into account shape, size, and color) has always been a fundamental aspect of the quality assessment of the crop. To increase the speed of the collection process, and to decrease the possible errors in the operation, several computer-based techniques (Neural networks) have been used to reduce the cost of the activity and improve its classification standards (Unal et al., 2022).

The fore-mentioned classification, especially on green beans, has usually been held out of hand and traditional methods with known limitations to assess damage or defects on the beans (Ansar et al., 2021; Kittichotsatsawat, Tippayawong e Tippayawong, 2022); lately, these methods are changing to some more advanced ones that use imaging and color characterization to evaluate more clearly the physical defects present on the bean. To improve the process, image analysis has been carried out through the decomposition of the samples in terms of the RGB scale and the application of a restoration factor to make reflectance calculations. The RGB scale is specified with red, green, and blue combination, each parameter defines the intensity of the color as an integer between 0 and 255 with 0 defining no presence of the parameter and 255 the highest intensity of the parameter (Refsnes Data, 2022). Afterward, multiscale Retinex techniques and alike, are used to classify the beans through a support vector machine and to find specific defects such as black coffee beans (García; Candelo-Becerra; Hoyos, 2019; Alamri et al., 2023).

The roast degree of a coffee bean deeply affects its physical properties (water load and activity, resting angle, specific mass, porosity, etc) and represents the possible quality of the final product; a roast degree analysis can visually show the changes of these properties through the change of color of the samples (Asociación de Café de Especialidad SCA, 2020; Oliveira et al., 2014). Roast time and temperatures determine several physical and chemical characteristics of coffee (sensible quality; anti-oxidizing activity; pH; and the final amount of sugar and phenolic compounds), the interaction of these two variables impact on the final color of the coffee bean that is used during its quality control process and determines its roast degree (Malaquias; Celestino; Xavier, 2018).

Roast Degree allows assessing the quality of the coffee bean, therefore, several techniques have been developed to determine it; some of them are focused on identifying the chemical markers through Discriminatory Analysis (Toledo et al., 2017), while others use the Agtron Scale to assess the roast degree with image processing based on the caramel infrared index. Some of these proposals use deep neural convolution networks and classification models based on real-time roast characterization that apply training data sets that include the RGB scale and the CIEL*a*b*scale; the latter having greater accuracy when ground roast coffee is used (Leme et al., 2019; Nasution; Andayani, 2017; Valerio Cubillo et al., 2016; Cuaya-Simbro et al., 2022).

In this context, this study aims to facilitate the determination of the roast level of ground coffee measured by the Agtron scale. By employing an optoelectronic color sensor to characterize the degree of roasting and correlating it with the RGB color model, we aim to support the accuracy of quality control measures from the beginning of the roasting phase.

2 MATERIAL AND METHODS

This research was carried out in three stages (Chathuranga et al., 2023): recollection of data, obtaining color representations in RGB, CIE L*a*b* and Agtron scales, and roast degree determination (Figure 1).

2.1 Recollection of data

Eight representative roasted coffee sample for each value of the Agtron Scale (Specialty Coffee Association - SCA, 2023) is selected during the roasting process from a total of 48 samples taken every 15 seconds and the samples are ground to the espresso standard (500 microns) using a BUNN grinder. Thereafter, the representative samples are scanned with a photosensor that translates the color information into light-specter values on RGB and CIE L*a*b* scales (International Color Consortium, 2010; International, Electrotechnical e Commission, 1999). The device employs an array of photodiodes equipped with color filters to detect the intensity of incident red, green, blue, and infrared light. These photodiodes are arranged in groups, each with filters of different colors (red, green, blue, and infrared), along with a clear (colorless) filter to measure the intensity of ambient light.

2.2 Color value representation

After collecting the values for RGB and CIE L*a*b* scales, they are compared to the Agtron Scale and validated through the SCA Agtron Roast Color Kit (SCA, 2017). For the process of obtaining the values of each sample on the Agtron scale, each sample sensed by the optoelectronic sensor is validated by a group of experts using the SCA Agtron Roast Color Kit. Subsequently, these results are compared with those obtained from commercial colorimeters.

2.3 Roast degree determination

As a result of the compiled data, it was established a relationship function between the Agtron and RGB scales, which has the Agtron value as the dependent variable and the most relevant RGB component (defined by the highest standard deviation value $\sqrt{\frac{\Sigma(x-\bar{x})^2}{n-1}}$) as the independent variable. The roast degree determination, as well as the characteristics of the evaluated sample, is made through the interaction of the color sensor used and the Agtron scale values; the above-mentioned function for roast degree determination is tested with a new dataset and these results are compared to the ones obtained with the SCA Agtron Roast Color Kit (SCA, 2017).

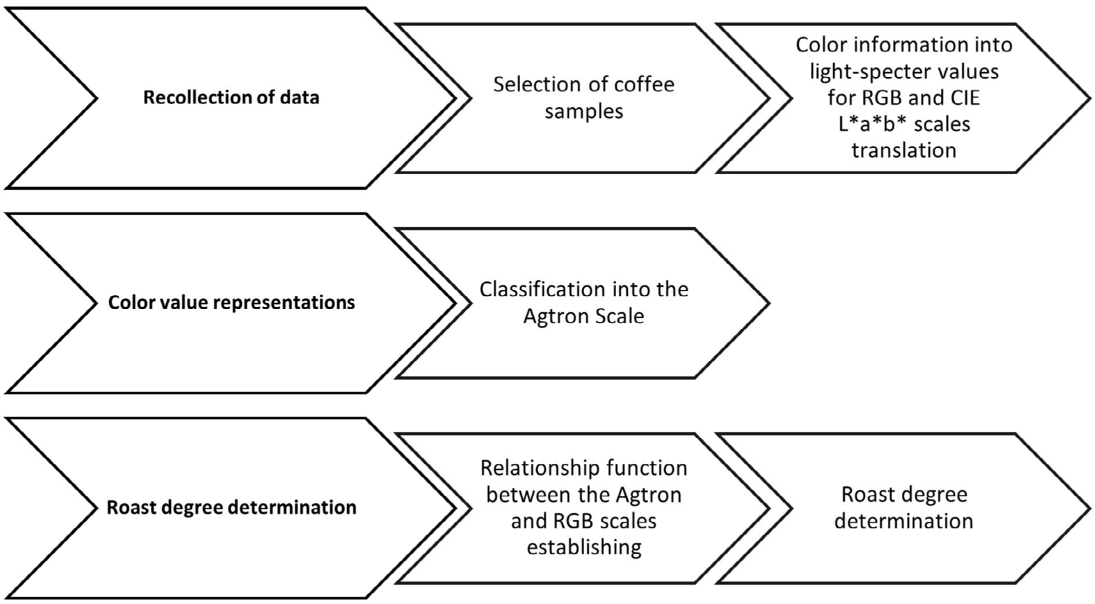


Figure 1: Process to determine the degree of roasting.

3 RESULTS

Each representative sample of ten roasting processes, obtaining a total of 80 samples, which represent the colors on the Agtron scale, is formed from 100g of roasted coffee beans that are ground to be characterized within a color scale.

3.1 Roasted ground coffee sample values in the RGB scale

The samples are color scanned and noted in terms of the RGB scale, its Agtron scale correspondence, and the graphical representation of the color as shown in Table 1.

Table 1: Roasted ground coffee samples' values for the RGB and Agtron scales.

Representative samples	R	G	B	Agtron	Color
1,9,17,25,33,41,49,57,65,73	229	207	158	95	
2,10,18,26,34,42,50,58,66,74	190	155	110	85	
3,11,19,27,35,43,51,59,67,75	154	114	75	75	
4,12,20,28,36,44,52,60,68,76	120	78	44	65	
5,13,21,29,37,45,53,61,69,77	96	58	34	55	
6,14,22,30,38,46,54,62,70,78	74	43	27	45	
7,15,23,31,39,47,55,63,71,79	55	34	27	35	
8,16,24,32,40,48,56,64,72,80	39	32	34	25	

3.2 Roasted ground coffee sample values in the CIE L*a*b* scale

The samples' scans are noted in terms of the CIE L*a*b* scale considering the values for luminosity, red-green coordinates, yellow-blue coordinates, clarity, color intensity, and hue angle, in relation to their Agtron correspondent and the graphical representation of the color as shown in Table 2.

3.3 RGB --- Agtron scale relationship

To determine the most influential RGB component related to the Agtron scale values, the variance of each one is calculated through their standard deviations (Table 3). The higher value is selected as the most relevant for roasted coffee: in this case 66.99 for the red RGB value.

Afterward, the relationship between both scales is established as a polynomial (Figure 2) where the RGB red component is the independent variable, and the Agtron values the dependent variable.

As a result of the polynomial correlation an $R^2 = 0.9984$ is obtained alongside the polynomial function (1) that would define the roast degree of coffee beans drawn from the scanned value for the RGB red component:

$$Y(x) = -0.00103434980244536x^2 + 0.634805680881433x + 2.92467847802944 \quad (1)$$

Similarly, the relationships for the green (2) and blue (3) components are demonstrated, with R-squared values of 0.9644 and 0.8316 respectively.

$$Z(x) = -0.00218189220462983x^2 + 0.862715098209914x + 7.67171721544513 \quad (2)$$

$$W(x) = -0.00377719259488241x^2 + 1.11268736613059x + 12.1660479659275 \quad (3)$$

3.4 CIE L*a*b* --- Agtron scale relationship

To ascertain the relationship between the CIE L*a*b* scale and the Agtron scale, the same procedure as for scale 3 is followed, yielding the values displayed in Table 4.

Similarly, Equation (4) indicates an alternative method for deriving the relationship between the scales by utilizing the conversion factors from the RGB scale to CIE L*a*b*, and employing the results obtained in (1) to transition to the Agtron scale.

Table 2: Roasted ground coffee samples' values for the CIE L*a*b* scale.

Representative samples	Luminosity (L)	Red-Green coordinates (a)	Yellow-Blue coordinates (b)	Clarity (c)	Color intensity (h)	Hue angle (d)	Agtron	Color
1,9,17,25,33,41,49,57,65,73	83.7	0.5	27.2	25.6	83.7	65/10	95	
2,10,18,26,34,42,50,58,66,74	66.2	6.8	28.5	29.1	77.0	65/10	85	
3,11,19,27,35,43,51,59,67,75	51.2	11.1	28.0	30.4	70.4	65/10	75	
4,12,20,28,36,44,52,60,68,76	37.1	14.3	26.9	30.5	61.9	65/10	65	
5,13,21,29,37,45,53,61,69,77	28.5	14.0	22.0	26.1	57.0	65/10	55	
6,14,22,30,38,46,54,62,70,78	20.9	12.4	16.4	20.5	50.4	65/10	45	
7,15,23,31,39,47,55,63,71,79	15.8	8.9	9.1	12.7	43.7	65/10	35	
8,16,24,32,40,48,56,64,72,80	13.2	3.4	0.1	2.7	37.1	65/10	25	

Table 3: RGB component standard deviation.

RGB Component	Standard Deviation
Red (R)	66.99
Green (G)	63.66
Blue (B)	47.82

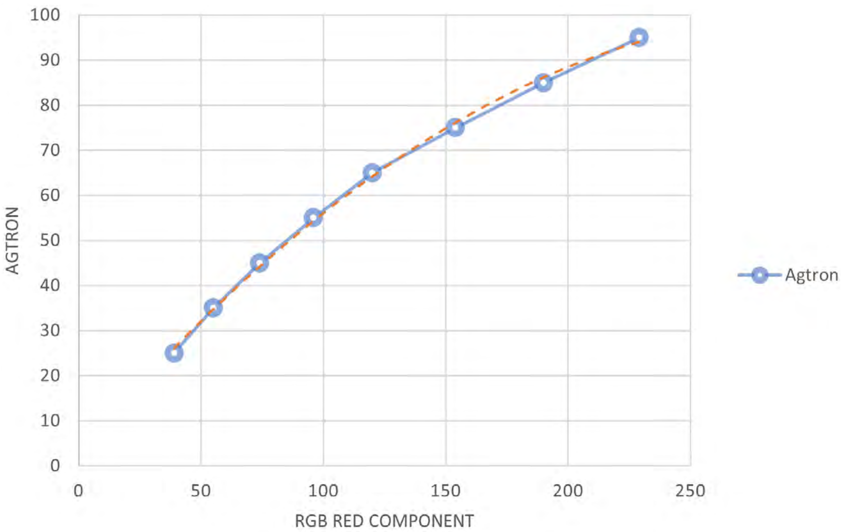


Figure 2: Agtron scale – RGB red component comparison.

Table 4: Relationship CIE L*a*b* with Agtron.

CIE L*a*b* Component	Relationship CIE L*a*b* - Agtron (f)	R^2
Luminosity (L)	$f(L) = 0.0124L^2 - 0.4756L + 17.3200$	0.9954
Red-Green coordinates (a)	$f(a) = 0.0099a^2 + 1.1402a - 18.9533$	0.9830
Yellow-Blue coordinates (b)	$f(b) = 0.0085b^2 + 1.4119b - 29.8360$	0.9817
Clarity (c)	$f(c) = -0.0113c^2 + 1.6834c - 32.3725$	0.9829
Color intensity (h)	$f(h) = 0.666h + 20.4158$	0.9774
Hue angle (d)	$f(d) = 6.5000$	N/A

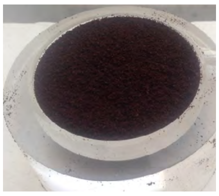
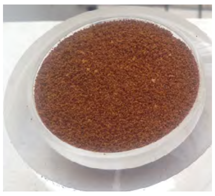
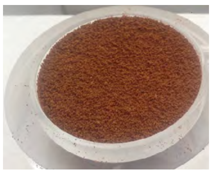
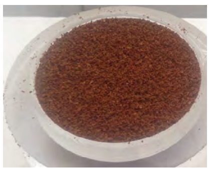
$$
\begin{aligned}
L^* = 116 * (((R/255) > 0.04045 \;?\; ((R/255 + 0.055)/1.055) ** 2.4{:}\ (R/255)/12.92) * 0.4124564 + ((G/255)\\
> 0.04045 \;?\; ((G/255 + 0.055)/1.055) ** 2.4{:}\ (G/255)/12.92) * 0.3575761 + ((B/255)\\
> 0.04045 \;?\; ((B/255 + 0.055)/1.055) ** 2.4{:}\ (B/255)/12.92) * 0.1804375) / 0.95047) - 16,\\
a^* = 500 * ((f(((R/255) > 0.04045 \;?\; ((R/255 + 0.055)/1.055) ** 2.4{:}\ (R/255)/12.92) * 0.4124564 + ((G/255)\\
> 0.04045 \;?\; ((G/255 + 0.055)/1.055) ** 2.4{:}\ (G/255)/12.92) * 0.3575761 + ((B/255)\\
> 0.04045 \;?\; ((B/255 + 0.055)/1.055) ** 2.4{:}\ (B/255)/12.92) * 0.1804375) / 0.95047) - f(((R/255)\\
> 0.04045 \;?\; ((R/255 + 0.055)/1.055) ** 2.4{:}\ (R/255)/12.92) * 0.2126729 + ((G/255)\\
> 0.04045 \;?\; ((G/255 + 0.055)/1.055) ** 2.4{:}\ (G/255)/12.92) * 0.7151522 + ((B/255)\\
> 0.04045 \;?\; ((B/255 + 0.055)/1.055) ** 2.4{:}\ (B/255)/12.92) * 0.0721750) / 1.00000)),\\
b^* = 200 * ((f(((R/255) > 0.04045 \;?\; ((R/255 + 0.055)/1.055) ** 2.4{:}\ (R/255)/12.92) * 0.2126729 + ((G/255)\\
> 0.04045 \;?\; ((G/255 + 0.055)/1.055) ** 2.4{:}\ (G/255)/12.92) * 0.7151522 + ((B/255)\\
> 0.04045 \;?\; ((B/255 + 0.055)/1.055) ** 2.4{:}\ (B/255)/12.92) * 0.0721750) / 1.00000) - f(((R/255)\\
> 0.04045 \;?\; ((R/255 + 0.055)/1.055) ** 2.4{:}\ (R/255)/12.92) * 0.0193339 + ((G/255)\\
> 0.04045 \;?\; ((G/255 + 0.055)/1.055) ** 2.4{:}\ (G/255)/12.92) * 0.1191920 + ((B/255)\\
> 0.04045 \;?\; ((B/255 + 0.055)/1.055) ** 2.4{:}\ (B/255)/12.92) * 0.9503041) / 1.08883)),\\
f(t) = t > (6/29) ** 3 \;?\; t ** (1/3)\,;\ (t / (3 * (6/29) ** 2) + 4/29)
\end{aligned}
\tag{4}
$$

3.5 Ground coffee beans' roast degree determination

To determine the roast degree 7 random samples of the 48 existing ones are taken for a roasting process, a photosensor is used to scan it and translate the data to the RGB scale; as the red value of the RGB scale is the most influential for the calculation, considering the R^2 values obtained, it would be the only one truly relevant when scanning the sample. Then, using the equation (1), such values are transformed into Agtron scale values that are easily interpretable and are directly related to the quality characteristics of the sample.

Table 5 shows the roast degree determination for the seven samples, their equivalence to the Agtron scale (SCA

Table 5: Ground coffee beans' roast degree determination.

N°	Sample	Red Component (RGB)	Roast Degree *Y (x)*	Agtron	Mean Absolute Error – MAE
1		76	45.1955	45	0,1955
2		37	24.9965	25	0,0035
3		64	39.3155	35-45	N/A
4		235	94.9820	95	0,0180
5		75	44.7169	45	0,2831
6		240	95.6995	95	0,6995
7		187	85.4632	85	0,4632
		Mean Square Error - MSE			0,1371

Agtron Roast Color Kit), and the Mean Absolute Error for each dataset.

The mean squared error (MSE) calculated from the evaluation of the samples, excluding the value not defined on the Agtron scale, is a mere 0.1371, which represents a low value, comparing the value of the Agtron scale and its corresponding value obtained through the $Y(x)$ function and considering that the Agtron scale only uses integer values. Furthermore, it can be seen how a particular value for the roast degree is obtained also in samples that do not have a specific value but that instead oscillate between the two categories as shown in sample 3; obtaining a value of 39,3155, which is not defined by default in the Agtron scale.

4 DISCUSSION

Having established a relationship between the RGB and Agtron scales, it is possible to apply it to other color scales such as the CIE L*a*b*, XYZ or CMYK, using a conversion factor from the RGB data; to successfully use the latter, it would be necessary to include all three components of the RGB scale. This relationship implies a simpler and more efficient implementation in terms of the number of variables and calculations, and the possibility of using more affordable devices to play the role of color scanning.

The obtained function, which relates the RGB and Agtron scales, shows a polynomic behavior and low MSE, this makes it suitable for systems with low processing specifications maintaining a high performance level. Through this process, such systems can achieve similar results to the ones with higher computing capacity and training time and datasets that involve image processing or AI.

Establishing a characterization of the roast degree through the red component of the RGB scale allows its measurement by systems with low processing specifications and its characterization showed that when going from light to dark tones, the greatest variation occurs in the red component, which allows characterizing the degree of roasting as a function dependent on this component. Likewise, the ability to easily determine the degree of roast through variations in the red component enables swift detection of changes in the roast state. This facilitates the achievement of a roast with a specific hue, ensuring the preservation of its intrinsic quality attributes. It is important to recognize that the color of the roasted bean is an indicator of its roast level, and in turn, the degree of roasting influences the values of various quality characteristics of the product.

5 CONCLUSIONS

Ground coffee beans' roast degree characterization is achieved through the RGB data collected by means of a color scanning that is later linearly related to the Agtron scale through a function with high accuracy with 0.1371 MSE. Furthermore, this relationship can describe intermediate values that are not fully stated on the Agtron scale but that require a correct characterization and classification of the analyzed sample.

The utilization of a function centered on the RGB red component has proven to be effective in achieving a more accurate characterization of the sample's roasting degree. Additionally, this approach simplifies the computational process, reducing the complexity of the function by minimizing the number of variables and calculations needed to describe the color accurately.

6 AUTHORS' CONTRIBUTIONS

SV wrote the manuscript and performed the experiment, DL supervised the experiment and co-work the manuscript, and JB review and approved the final version of the work, SV conducted all statistical analyses.

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