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Authentication of indigenous Brazilian specialty canephora coffees using smartphone image analysis

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ABSTRACT

The prevention of coffee fraud through the use of digital and intelligence-based technologies is an analytical challenge because depending on the adulterant, visual inspection is unreliable in roasted and ground coffee due to the similarity in color and texture of the materials used. In this work, a 3D-printed apparatus for smartphone image acquisiton is proposed. The digital images are used to authenticate the geographical origin of indigenous canephora coffees produced at Amazon region, Brazil, against canephora coffees from Espírito Santo, Brazil, and to capture the adulteration of indigenous samples. The results evidenced that the technology is favorable to identify the geographical origin and adulteration with multiple substances using smartphone technology. Pure coffees were adulterated with arabica coffee, spent coffee ground, low-quality Canephora coffee, coffee husks, açaí, corn, and soybean in increasing proportions of 10, 20, 30, 40, 50, 60, and 70 %. These adulterants were roasted and grounded similarly to Canephora coffees to mimetize a highly-sophisticated fraud. The images were converted into Red-Green-Blue (RGB) fingerprinting and used as analytical response to construct Data-Driven Soft Independent Modeling of Class Analogy (DD-SIMCA) models. A total of 95 % of all target and non-target samples in the test set were correctely identified, aiding producers and consumers in ensuring accurate labeling and supporting traditional communities economically and culturally. Smartphone-based method demonstrated potential to innovate the coffee safety control representing a new analytical tecnology.

1. Introduction

Over time, food fraud has evolved with scientific and technological progress. Recently, there is been a surge in deceiving practices aimed at verifying where food comes from, i.e., its geographical origin. This focus on food origin has grown due to sensory qualities, health endorsements, trust in local sourcing, and media influence. While claims about food origin typically do not affect health, they can constitute significant fraud. Consumers often pay more for goods labeled with specific regions, assuming traditional and healthier methods. In this context, Geographical Indications (GIs) offer distinctive, high-value products, serving as a tool for governments and producers to combat food fraud, enhance product worth, and satisfy consumer desire for quality-assured labeling (Wilkinson et al., 2017). Successful international examples (Agostino & Trivieri, 2014; Dogan & Gokovali, 2012), including coffee (Barjolle et al., 2017; Neilson et al., 2018), are well-documented.

In recent years, there has been a notable surge in the global coffee market, with South America, particularly Brazil, assuming a prominent role. The escalation in bean prices has provided a substantial boost to the economies of major coffee-producing nations. Among the species catalogued within the Coffea genus, *Coffea arabica* and *Coffea canephora* are the most significant due to their distinctive attributes and adaptability. *Coffea arabica* is renowned for its smoother, more nuanced flavor profile with reduced bitterness, thriving in high-altitude regions with specific climatic conditions. Conversely, *Coffea canephora* is characterized by higher caffeine content, greater resilence to pests and diseases, and a

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preference for lower altitudes. It is frequently utilized in espresso blends and instant coffee due to its robust, bitter flavor and dense crema. The interplay of flavor diversity, cultivation versatility, and economic considerations has solidified their preeminence in the coffee industry. From both consumer and industry perspectives, specialty coffee is distinguished by its exceptional flavor and aroma, derived from high-quality beans that meets rigorous aesthetic and sensory evaluation standards, contrasting with common coffee, which adheres to lower quality benchmarks (Baqueta, Diniz, et al., 2024; Freitas et al., 2024). Various factors, ranging from cultivation methodologies to consumer preferences, exert a significant influence on coffee quality. In susch a scenario, the Coffee Quality Institute (CQI) and the Uganda Coffee Development Authority (UCDA) collaboratively work to establish tasting protocols, specifically tailored for *Coffea canephora*, within the domain of specialty coffee production (Freitas et al., 2024; Lingle & Menon, 2017; Zani Agnoletti et al., 2023).

In 2021, the National Institute of Industrial Property (INPI, Brazil) granted Geographical Indication (GI) seals to conilon and robusta coffees, varieties of *C. canephora*. Conilon from Espírito Santo obtained an Indication of Origin, while Amazon robusta from Rondônia was designated as Matas of Rondônia with Denomination of Origin. This indicates the rising significance of *C. canephora*, influencing worldwide coffee production and consumption, while also paving the way for conilon and high-quality robusta coffees in the specialty coffee industry (Baqueta, Alves, et al., 2023; Baqueta, Marini, et al., 2023; Zani Agnoletti et al., 2023).

In the filed of analytical methodologies for the Brazilian *C. canephora* quality evaluation, several approaches have been reported, including bromatologial, chromatographic, and sensory analysis (de Souza Costa et al., 2024), liquid chromatography/high-resolution mass spectrometry (LC-HRMS) (Brand et al., 2024), ultra-performance liquid chromatography (UPLC) (Viencz et al., 2023), electrospray ionization-linear ion trap quadrupole-Orbitrap-high-resolution mass spectrometry (ESI-LTQ-Orbitrap-HRMS) (Lemos et al., 2020), flame atomic absorption spectrometry (FAAS) (Baqueta, Costa-Santos, et al., 2024), ultraviolet–visible spectroscopy (Caldeira et al., 2024), mid-infrared (MIR) spectroscopy (Zani Agnoletti et al., 2023), portable and benchtop nir-infrared (NIR) spectroscopy (Baqueta, Alves, et al., 2023; Baqueta, Marini, et al., 2023), in addition to the data fusion from multiple analytical techniques (in this case, proton nuclear magnetic resonance (^{1}H NMR), FAAS, handheld NIR, benchtop NIR, and MIR spectroscopies) (Baqueta, Valderrama, et al., 2023). However, most of these methods necessitate extensive sample preparation, which is both time-consuming and labor-intensive, with the exception of non-destructive MIR and NIR spectroscopies. Furthermore, while all methods incur costs associated with instrument acquisition and/or maintenance, the handheld NIR spectrophotometer remains an exception.

Regarding non-destructive analysis, digital images obtained from simple image capturing devices such as smartphones, webcam, digital cameras and scanners have provided a distinct type of analytical approach known as Chemometrics-assisted Color Histogram-based Analytical System (CACHAS) (Gonçalves Dias Diniz, 2020). CACHAS captures analytical data on sample matrix complexity through conventional digital images, extracting color histograms that serve as a fingerprint signature by depicting pixel frequency distributions as a function of each color component. This has been already successfully applied for discriminating coffee adulteration by addition of husks and sticks (Souto et al., 2015) and authenticating Gourmet coffee (de Araújo et al., 2021). In such a scenario, there is a future trend of using non-destructive fingerprinting techniques for exploring the Food Quality 4.0 concept, which involves employing Industry 4.0 technologies, such as sensors, artificial intelligence, and data analytics, to enhance food quality assessment. It aims to achieve rapid, reliable, and objective evaluations, improving efficiency, reducing labor, and advancing food safety and quality in a more automated and integrated manner (Hassoun et al., 2023). One way to achieve this is employing smartphone-based imaging (Amani et al., 2022; Caramês et al., 2021; Meenu et al., 2021) and 3D printing in the fabrication of detection systems (Carrasco-Correa et al., 2021; dos Santos et al., 2022). A 3D-printer fabricates three-dimensional objects through additive manufacturing by systematically layering material based on a digital model. The model, generated via computer-aided design (CAD) software, is sliced into thin layers by specialized software, converting the design into executable instructions. The printer then extrudes materials like plastic, resin, or metal, depositing them layer by layer to construct the object (Gibson, Rosen, & Stucker, 2010). Consequently, the 3D-printed apparatus is engineered to standardize conditions for smartphone image capture, ensuring consistent lighting, distance, and angle. This optimization enhances both the quality and reliability of the smartphone's digital image, which is a two-dimensional pixel matrix specified through a color space, forming a digital depiction of the scene or object captured by the camera (Carrasco-Correa et al., 2021; dos Santos et al., 2022).

Since GI seals can serve to address existing forms of social inequality and promote the inclusion and political empowerment of the most marginalized participants within commodity value chains (Coombe, 2018), this work proposes, for the fisrt time, the development a CACHAS method that employs a 3D-printed apparatus for smartphone image analysis of indigenous Brazilian specialty Canephora coffees. For this purpose, Red-Green-Blue (RGB) fingerprinting was used as analytical response to construct Data-Driven Soft Independent Modeling of Class Analogy (DD-SIMCA) models. The predictive ability of these models was subsequently assessed to authenticate the geographical origin of Canephora specialty coffees cultivated by indigenous farmers in Rondônia, comparing them against the renowned Canephora specialty coffees from Espírito Santo. Additionally, the models were tested for their ability to detect adulteration, including the addition of Arabica coffee, spent coffee ground, low-quality Canephora coffee, coffee husks, açaí, corn, and soybean. These adulterants were roasted and grounded similarly to the specialty Canephora coffees to mimetize a highly-sophisticated fraud.

2. Materials and methods

2.1. Coffee samples

A total of 200 pure specialty Canephora coffee samples, with 100 samples each originating from the Amazonian Robusta variety cultivated by indigenous farmers of Rondônia, and the Conilon variety produced in Espírito Santo, were studied. All pure samples were generously provided by the Brazilian Company of Farming Research (EMBRAPA, Research Center of Rondônia). These samples underwent medium roasting in a Probat sample roaster following the protocol outlined by the Uganda Coffee Development Authority (UCDA, 2010), with temperatures ranging from 160 °C to 190 °C over a duration of 7.5–9 min.

2.2. Preparation of the adulterated coffee samples

Corn and soybeans were purchased from local markets in Campinas, São Paulo, Brazil, while Arabica coffee cultivated in Pedregulho, São Paulo, Brazil, and low-quality Canephora coffees from Londrina, Paraná, Brazil, were provided by coffee industries. Canephora coffee husks were supplied by EMBRAPA Rondônia. Pulped açaí seeds, obtained from a local manufacturer in Belém, Pará, Brazil, were kept frozen at −12 °C until required. All raw materials underwent roasting in a manner similar to pure samples, with variations in temperature and time to achieve a comparable roasted coffee profile based on previous studies (Milani et al., 2020; Reis et al., 2017). Spent coffee grounds, obtained from water extraction of authentic coffee samples, were dried in a convection oven (Model 520-C, Fanem, São Paulo, Brazil) at 100 °C for 5 h to attain a moisture content similar to ground roasted coffee (~5 % w w^{-1}). The roasted coffees and adulterants were milled and then passed through a 20-mesh sieve for particle size standardization. Pure indigenous coffee

samples were randomly mixed with only one adulterant in duplicate at the proportions of 10 %, 20 %, 30 %, 40 %, 50 %, 60 %, and 70 % w w^{-1}, resulting in a total of 100 adulterated indigenous coffee samples.

2.3. CACHAS procedure

2.3.1. 3D-printed apparatus

In order to standardize lighting conditions for image acquisition, a 3D-printed chamber was developed using a Creality Ender 5 Pro printer (Kwai Chung, Hong Kong). It consists in a black box with a side tray for sample introduction and a two-part lid, which has a sliding slit for positioning the smartphone camera (Fig. 1**a**) and two angled supports for white light-emitting diode (LED) strips (6500 K) placed in an appropriate angle (Fig. 1**b**). This feature was designed so the chamber can be used with any smartphone model, regardless the position of its camera. The angles for the LED strips are optimized for projecting the light beams exactly in the middle of the tray and slightly below the top of the sample holder, avoiding shadow casting (Fig. 1**c**). Furthermore, the two LED strips can be independently turned on and off, allowing the operator to choose what is the best lighting for image acquisition. The chamber was designed using Fusion 360® (Autodesk) and printed in black polylactic acid (PLA) with 0.2 mm resolution and minimum infill and number of walls configurations, set up during the slicing process using the Cura® software (Ultimaker). After wiring the LED strips to a power source and the appropriate switches, the lid was attached to the chamber using double-sided tape, allowing easy access to the inside of the chamber for cleaning and maintenance if needed. The project of 3D-printed apparatus is freely available in https://www.thingiverse.com/thing:6549900.

2.3.2. Image acquisition and chemometric procedures

Digital images of all samples were acquired in triplicate using an android smartphone, model Redmi Note 11, 4 GB RAM, 128 GB ROM, Xiaomi (China), with 50 megapixels, and 8165 × 6124 pixel resolution. Average RGB histograms (from the triplicates) of each sample were obtained from a circular region of interest (ROI) located in the center of each image using the free downloadable software ImageJ® 1.44p.

An exploratory analysis of the natural grouping of the samples was initially using Principal Component Analysis (PCA). Subsequently, a DD-SIMCA (Zontov et al., 2017) model was constructed using exclusively the target samples, i.e., indigenous Brazilian specialty Canephora coffees from Rondônia. For this, significance level of 0.01 was adopted for the type I and II errors and the significance of outliers, with acceptance areas determined via the robust mode of the chi-square distribution. The optimization of the number of principal components (PCs) in DD-SIMCA was guided by the criterion of achieving the optimal balance of true positive cases across both the construction and test phases.

To ensure that all samples represent the same error percentage (i.e., one misclassified sample implies 1 % error) and avoid unfair evaluation of unbalanced test sets, Procrustres Cross-Validation (PCV) was used to create a new pseudo-validation set, emulating a new set of objects taken from the target samples. This enables the evaluation of sensitivity during the test phase without removing any samples from the original target set, thus assessing the robustness of the developed model (Pomerantsev & Rodionova, 2021). Sensitivity measures the proportion of target samples (viz. 100 pure indigenous samples in the training set and 100 PCV pure indigenous samples in the test set) accurately projected within the acceptance area (i.e., true positives) in both the construction and test phases. Additionally, specificity of the DD-SIMCA model was evaluated using the proportion of non-target samples (viz. 100 pure Espírito Santo samples and 100 adulterated indigenous samples) correctly projected outside the acceptance area (i.e., true negatives) in the test phase. Finally, the efficiency of the DD-SIMCA model was calculated as the geometric mean of sensitivity and specificity in both the construction and test phases (de Araújo Gomes et al., 2022).

All chemometric procedures were performed using Matlab® 2018b (Mathworks Inc.). PCA was downloaded from https://michem.unimib.it/download/matlab-toolboxes/pca-toolbox-for-matlab/, PCV from https://github.com/svkucheryavski/pcv and DD-SIMCA from https://github.com/yzontov/dd-simca.

3. Results and discussion

3.1. Exploratory analysis

Fig. 2**a** depicts the mean RGB histograms derived from analyses of pure indigenous coffee (in blue), pure Espírito Santo coffee (in red), and adulterated indigenous coffee (in yellow) samples. It is evident that

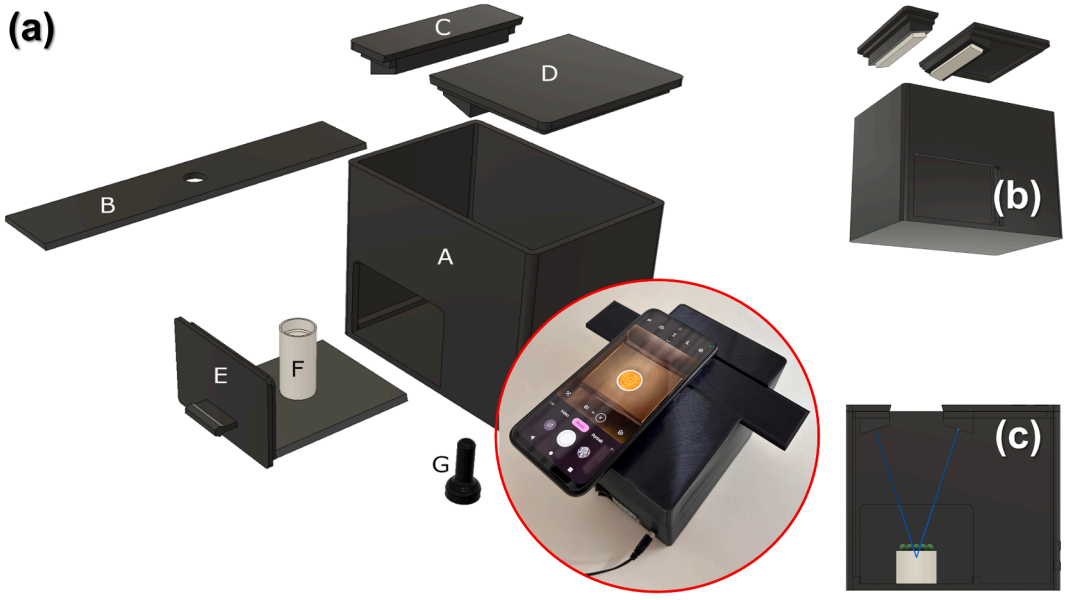

Fig. 1. (a) Exploded view of the box, showing the main body (A), adjustable slit for mobile camera (B), short and long lids (C and D, both with angled supports for LED strips), sample tray (E), sample holder (F) and sample compactor (G). Details of the (b) disposition of the LED strips under the angled lids (white blocks) and (c) representation of the light beams (blue lines). A photograph of the smartphone camera integrated into the analytical system, capturing an image of a coffee sample, is presented in the red inset.

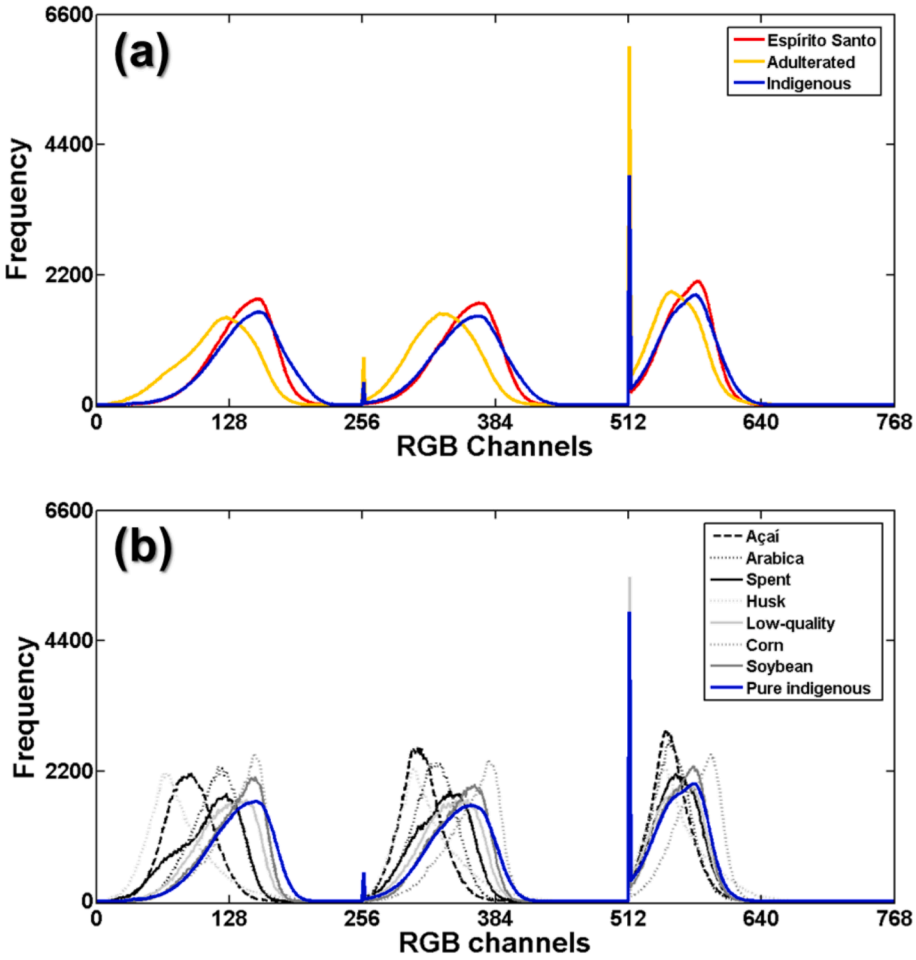

Fig. 2. (a) Average RGB histograms of pure indigenous coffees (in blue), pure Espírito Santo coffees (in red), and adulterated indigenous coffees (in yellow). (b) Comparison between the average RGB histograms of pure indigenous coffees and their adulterants: Arabica coffee, spent coffee ground, low-quality Canephora coffee, coffee husks, açaí, corn, and soybean.

while the profiles of pure indigenous and Espírito Santo coffees exhibit substantial resemblance, they differ slightly in terms of frequency distribution. Conversely, adulterated indigenous samples tend to exhibit diminished saturation levels in the RGB channels. This observation is corroborated by comparing the mean histograms of the seven adulterants with that of pure indigenous coffee, as depicted in Fig. 2**b**. Notably, histograms corresponding to soybean and low-quality Canephora coffee closely resemble that of pure indigenous coffee. Indeed, the presence of adulterants and/or defects shifts the frequencies to less saturared color tones (i.e., to the left), which is in line with the findings of de Carvalho Polari Souto et al. (2015) and de Araújo et al. (2021).

To perform an exploratory analysis of the data, Principal Component Analysis (PCA), which is a well-known unsupervised pattern recognition technique used to reduce the dimensionality of data while preserving as much variance as possible, has been used. For this, a covariance matrix is calculated to understand how the features vary with respect to each other, taking into account the linear relationships between the variables. PCA then computes the eigenvalues and corresponding eigenvectors of the covariance matrix. The eigenvectors (principal components (PCs)) represent directions in the feature space, and the eigenvalues indicate the amount of variance carried in each direction. The principal components are sorted by the magnitude of their eigenvalues, with the first few components capturing the most variance. By focusing on these first PCs, PCA simplifies the data, making it easier to identify patterns, clusters, or trends without being influenced by noise or less significant information. The PCA score plots shown in Fig. 3**a** and **b** accounted for 94.59 % of the explained variance across the first four principal components (PCs), distinctly confirming the favorable separation trend of adulterated indigenous coffees (yellow circles), whereas pure indigenous (blue circles) and Espírito Santo (red circles) coffees exhibit greater overlap. To address this issue, one-class classification via DD-SIMCA was conducted, as detailed in the subsequent section.

3.2. Authentication

Table 1 shows the confusion matrix with the sensitivity, specificity, accuracy, and efficiency values obtained by DD-SIMCA for the authentication of indigenous Brazilian specialty Canephora coffees.

As seen in Table 1, the RGB-based DD-SIMCA model exhibited a very good performance, correctly projecting 98 % of the pure indigenous coffee samples (blue circles) within the acceptance area delimited by the established blue line considering an α-value of 0.01. Only 2 extreme samples (gray squares) were projected out of the acceptance area, while no one sample fall outside the second cut-off level (gray line) determined to be used as the outlier border (Fig. 4**a**). To maintain the representativeness of the target class, the PCV algorithm was employed to validate the constructed model, achieving a high sensitivity of 95 % in the test phase (Fig. 4**b**). The specificity of the model was tested against pure Espírito Santo (n = 100) and adulterated indigenous (n = 100) coffee samples. In both the cases, DD-SIMCA correctly recognized 95 samples of each category as not belonging to the target class. Only 5 pure Espírito Santo coffee samples (red circles) (Fig. 4**c**) and 5 adulterated indigenous coffee samples (yellow circles) (Fig. 4**d**) were misprojected inside the acceptance area. All misclassifications were depicted as green circles in

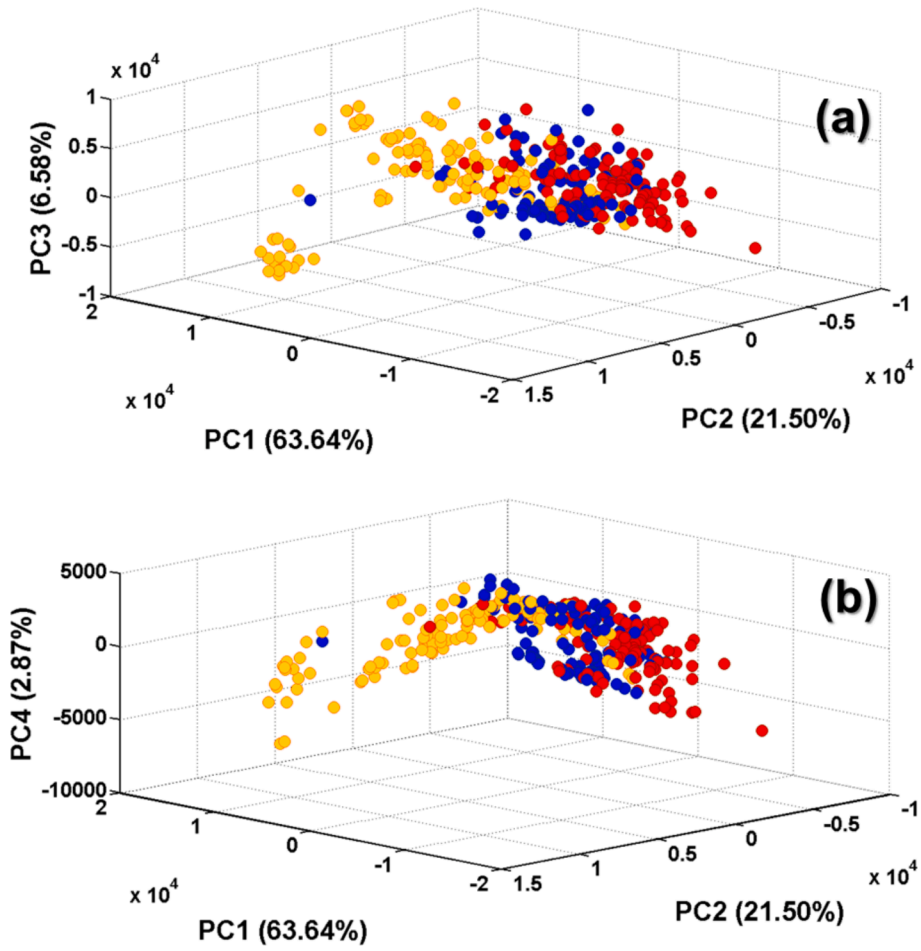

Fig. 3. Plots of PCA scores obtained from the RGB histograms of pure indigenous coffees (blue circles), pure Espírito Santo coffees (red circles), and adulterated indigenous coffees (yellow circles): (a) PC1vs PC2 vs PC3, and (b) PC1vs PC2 vs PC4.

Table 1
Results, with the confusion matrix, sensitivity, specificity, accuracy, and efficiency values, obtained by DD-SIMCA for the authentication of indigenous Brazilian specialty *Canephora* coffees.

DD-SIMCA					
Model parameters:		DoF (SD): 9 DoF (OD): 100 α, β, and γ: 0.01			
Model performance:		TRAINING	TEST		
		Indigenous coffees	PCV target coffees	Espírito Santo coffees	Adulterated coffees
Matrix confusion	Within the acceptance area	98	95	5	5
	Outside the acceptance area	2	5	95	95
Figures of merit	Sensitivity	98 %	95 %	–	–
	Specificity	–	–	95 %	95 %
	Accuracy	96 %			
	Efficiency	95 %			

DoF: degrees of freedom; SD: score distance; OD: orthogonal distance; α: type I error; β: type II error; γ: outlier significance.

Fig. 4.

Regarding the literature, only Baqueta, Marini, et al. (2023) and Zani Agnoletti et al. (2023) employed DD-SIMCA to authenticate Canephora coffees. Baqueta, Marini, et al. (2023) used a portable NIR spectrophotometer to authenticate the geographical origin of Robusta Amazônico coffees, which are produced in the delimitation of the GI seal "Matas de Rondônia" and includes indigenous and non-indigenous producers from Rondônia. In this case, all GI Robusta Amazônico coffees were correctly authenticated against other non-GI Canephora coffees, achieving 100 % of sensisivity and specificity. On the other hand, Zani Agnoletti et al. (2023) employed MIR spectroscopy to authenticate the Apoatã coffees, which are one of the botanical varieties of Robusta Amazônico coffees under the "Matas de Rondônia" GI seal, along with a hybrid (Conilon × Robusta) variety. They achieved sensitivities of 96.4 % and 100 % for the training and test sets, considering only the Apoatã coffees as the target class. The classification of non-target classes yielded specificities

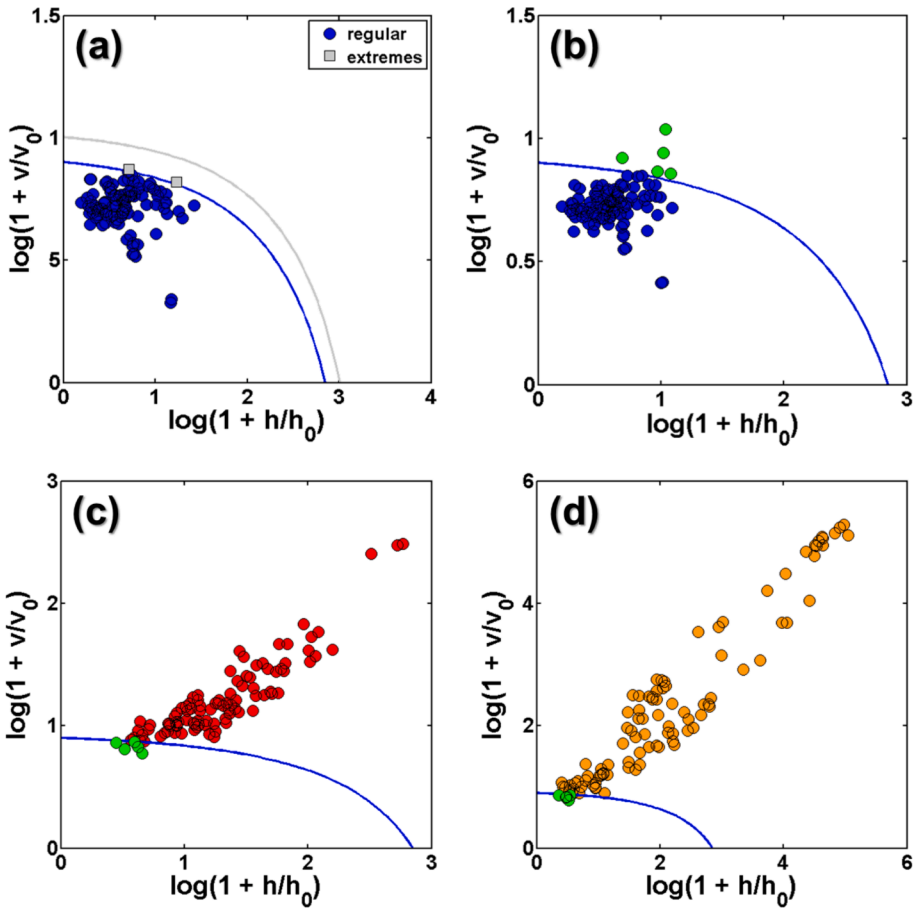

Fig. 4. Acceptance plots obtained by DD-SIMCA using the RGB histograms for the training set containing exclusively pure indigenous coffees (a), along with the test set, including procrustes crossvalidated target samples (b), Espírito Santo coffees (c), and adulterated indigenous coffees (d).

of only 16.2 % for the Robusta samples, Bahia had 45.8 %, Minas Gerais had 26.7 %, and São Paulo 10.0 %. However, Conilon achieved 100 % specificity. Therefore, the results obtained in this proposed work are comparable to the results found elsewhere.

It is worth noting that our study did not aim to develop a discriminant model for identifying adulteration types. Discriminant classification techniques require prior knowledge of defined classes, assigning unknown samples to predefined classes even when lacking similarity, typically necessitating over 30 samples per class for accurate modeling. However, such methods are unsuitable for authentication problems, as they fail when samples fall outside the predefined classes. In contrast, DD-SIMCA differs by modeling the target class exclusively using representative samples, constructing acceptance boundaries based on analytical signals. During the prediction step, unknown samples are assessed for class membership based on their chemical and/or physical features, determining whether they belong to the target class. In other words, this approach exclusively models the target class (e.g., "pure/unadulterated" samples) and tests the model's predictive capability against all other samples, regardless of adulterant type or quantity, making it an effective tool for authentication purposes (Rodionova, Titova, & Pomerantsev, 2016).

While sensory analysis has detected adulterations as high as 20 % (Ameca-Veneroso et al., 2021; Toci, Farah, Pezza, & Pezza, 2015), various analytical methods, including microscopic, DNA-based, chromatographic, and spectroscopic techniques, have identified adulterations below 10 % (Baqueta, Diniz, et al., 2024; Toci, Farah, Pezza, & Pezza, 2015). However, sensory analysis is notably subjective, whereas these instrumental techniques, despite providing detailed chemical insights, demand expensive equipment, regular maintenance/calibration, and highly trained personnel. In contrast, smartphone-based CACHAS approaches are limited to providing only physical information. Nevertheless, the proposed method was capable of detecting adulterations as low as 10 % in a non-subjective and highly reproducible manner. This makes it a promising, rapid, and non-destructive screening tool for detecting common adulterants at levels above 10 %, although concentrations between 1 % and 10 % still require molecular-based instrumental methods, particularly in cases of sophisticated fraud involving adulterants with similar roasting levels or highly comparable substances, such as coffee from different varieties or geographical origins.

4. Conclusions

This work demonstrated that the digital image-based authentication of indigenous Canephora coffees regarding their geographical origin and adulteration can serve as an effective preliminary authentication tool, aligning with Green Food Analysis principles. The excellent predictive capability of the DD-SIMCA model using the RGB histogram, recognining correctly 95 % of all target and non-target samples in the test set, aiding producers and consumers in ensuring accurate labeling and supporting traditional communities economically and culturally. Therefore, developing eco-friendly analytical methods fosters environmental resilience. Moreover, confirming GI certifications promotes equity, sustainability, and contributes to the decolonization and self-determination of these marginalized groups.

CRediT authorship contribution statement

Michel Rocha Baqueta: Writing – original draft, Visualization,

Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Matheus Pereira Postigo:** Writing – original draft, Software, Resources, Methodology, Investigation, Conceptualization. **Enrique Anastácio Alves:** Methodology, Resources. **Venancio Ferreira de Moraes Neto:** Methodology, Formal analysis. **Patrícia Valderrama:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis. **Juliana Azevedo Lima Pallone:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Paulo Henrique Gonçalves Dias Diniz:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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