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DETERMINATION OF CACAO QUALITY USING THE MUMFORD-SHAH FUNCTIONAL ALGORITHM AND IMAGE SEGMENTATION

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SUMMARY

One of the major issues in the agricultural industry is cocoa quality determination that may be based on subjective sensory assessment techniques that may cause inconsistency and losses after harvesting. The following research will solve the set of issues by taking the Mumford-Shah functional algorithm with the image segmentation, to evaluate the quality of cocoa at various stages of development: un-ripe, ripe, and diseased. The operation of the segmentation is performed on MATLAB simulation, and the images are processed to measure the primary metrics like how many regions they have, the average area, the average perimeter, and the average eccentricity. The outcomes of the segmentation indicate a clear difference in such measures in the three stages of cocoa growth. In the case of unripe cocoa there are 997 regions and the average region area is 10,509.80 pixels, the average perimeter is 18.40 pixels and the average eccentricity is 0.20. In case of ripe cocoa, there are 768 regions with the average area of 13,997.49 pixels, perimeter of 24.57 pixels, and the average eccentricity of 0.21. The diseased cocoa had 1,705 regions with a mean area of 5,936.61 pixels, mean perimeter of 11.68 pixels and with a mean eccentricity of 0.21. The discussion has shown that the Mumford-Shah algorithm offers an accurate means of grading cocoa quality and has been shown to offer major benefits over the conventional sensory assessment procedures, post-harvest losses and quality control in cocoa production.

Key words: *cocoa quality, mumford-shah algorithm, image segmentation, agricultural image processing, quality control, MATLAB simulations, organoleptic characteristics.*

INTRODUCTION

Historically, high-quality agricultural exports have been highly challenging for all countries, and even more so when we are talking about cocoa (Therobroma cacao), since it is one of the main products with world production of more than 4,72 million tons. [1] [2]

Cocoa is native to the Amazon basin, and Peru is one of the main countries that has the largest genetics of this cultivation providing more than 60% of the cocoa varieties cultivated by farmers around the world [1]. Its quality stands out for its organoleptic characteristics.

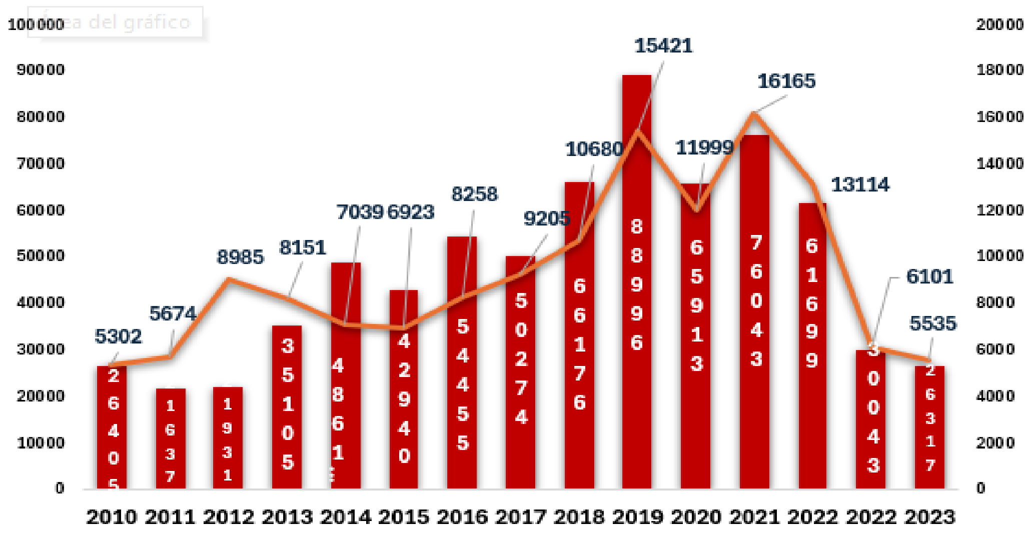


Figure 1. Adapted from midagri database

Figure 1 shows in the bars the tons produced in Peru in the years 2010 to 2023 and with a price trend in dollars of cocoa.

The value of Peruvian cocoa exports experienced a significant increase of 305.9% between 2023 and 2024, rising from 122 million to 495 million US dollars. The main export destinations were:

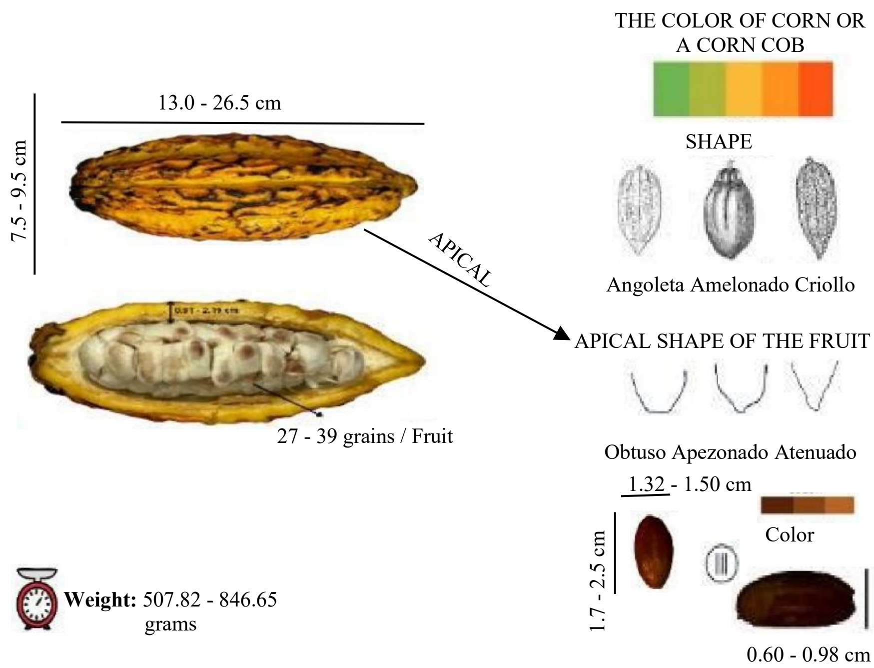


Figure 2. Organoleptic characteristics we use color and texture, own elaboration

Malaysia: 98 million USD, Indonesia: 86 million USD, Netherlands: 57 million USD y Belgium / Luxembourg: 55 million USD [3].

The quality of cocoa is based on its correct harvesting, this activity is carried out entirely by hand, in other words, cocoa farmers identify the morphological and organoleptic characteristics through their senses (Figure 2) [4].

To determine the quality or verification of maturity, the indicated sensory characteristics used by cocoa producers must be taken into account, which can lead to considerable inconsistencies [5]. In addition to having a negative impact on the health of consumers, it also has repercussions on the economy of farmers, since, by not harvesting the final product on time, they completely lose the fruit. [4]

Due to optimization problems, it is planned to specify a technology with suitable characteristics for its determination. Technological advances, which progress rapidly every year, allow us to find optimal values for the recognition and evaluation of quality. [6] [7]

Key Contribution

- Mumford-Shah functional algorithm is an image segmentation algorithm that will be applied to the cocoa images, which offers a more precise and objective analysis of cocoa quality.
- Comparison of the algorithm performance in detecting cocoa by the various stages of development including: unripe, ripe and diseased, using the relevant metrics of the image including: area, perimeter and eccentricity.
- Provision of the effectiveness of the Mumford-Shah algorithm on the examples of MATLAB simulating the algorithm, which indicates its ability to minimize post-harvest losses and manage cocoa quality better.

The paper is presented in the following way: Section 2 gives a comprehensive literature review of the quality determination methods of cocoa and image segmentation methods. Section 3 provides the methodology of the work, including the Mumford-Shah functional algorithm and image segmentation process. The discussion of the findings of the experiments (its important metrics, comparisons) can be found in section 4. Lastly, Section 5 had a conclusion of the paper summarizing the findings, limitations and the future research directions.

LITERATURE REVIEW

Manual sensory assessment has also been used in cocoa quality assessment, and this can be prone to inconsistencies as well as subjective assessment. Image processing methods especially image segmentation has been considered over the recent years in order to automate this process to enhance accuracy and efficiency [21]. A number of studies have worked on the application of image segmentation in determining the quality of cocoa judging by visual features including color and texture. Vergel et al. (2022) [5] and Bonilla and Hubert (2022) [2] also show how segmentation can be utilized to analyze cocoa, and such studies tend to disregard the fact that cocoa can be segmented into unripe, ripe, and diseased at different stages of development [22]. This poses a loophole which the present study will aim to fill using the Mumford-Shah functional algorithm that has been proven to be highly accurate in identifying edges and cutting images into meaningful components to cocoa quality determination [23].

In 1989, the Mumford-Shah functional algorithm was developed, and it has been extensively applied in computer vision due to its effectiveness in identifying the edges and segmentation of more complicated images. Although the algorithm has been able to be used in facial recognition and in low-light settings, there have been few uses of the algorithm in agricultural produce such as cocoa. Other recent studies such as the one by Kang and Hua (2023) [6] have applied the Mumford-Shah algorithm to improve the segmentation process, yet they have not been tested in a large-scale on-farm setting. Also, the problems with cocoa image segmentation, which is vastly different depending on the ripeness and disease, is not very discussed yet. The study seeks to fill this gap by testing the Mumford-Shah algorithm according to the real-life agricultural settings using MATLAB simulations to partition cocoa images and examine their quality in a better manner [24].

Image segmentation has been done previously in the agricultural research, but research on segmentation of cocoa quality with advanced segmentations is still developing. The present work closes this gap by applying the Mumford-Shah algorithm to categorize cocoa in terms of its organoleptic characteristics to enhance the precision of the quality control and the effectiveness of the post-harvest operations. By so doing, the study will contribute towards a more valid method of assessing the quality of cocoa which will result in less post-harvest losses and enhance the exportation of cocoa.

In the search and collection process, academic research in the scientific field was selected. Using terms and keywords in Spanish: "segmentation", "images", "quality", "cocoa", "algorithm", "functional", "Mumford-Shah" and in English: "Cocoa", "Quality",

"Mumford-Shah"," functional"," algorithm", "Image"," Segmentation"; the following search equations were used by journal as shown in the Table 1.

Table 1. Journal search equations

Magazine	Search equation
Scopus	"Cocoa AND Quality" + "Mumford-Shah AND functional algorithm" + "Image AND Segmentation
Scielo	"Image segmentation "+" Mumford-Shah functional algorithm"
Sciences	"Cocoa quality "+" image segmentation"
IOPScience	"Cocoa quality" + "Mumford-Shah functional algorithm"

Source: own elaboration

The results of the literature review in the search engines gave a total of 245 scientific articles related to the research keywords. Scopus provided the largest number of results with 188 articles, followed by Science with 18, Scielo with 23 and IOPScience with 16 articles. In addition, a total of 24 scientific articles and the publication of the report of the Central Reserve Bank of Peru (BCRP) were filtered and selected for this research as shown in the Table 2.

Table 2. Table data collection by keywords

DATA BASE	TOTAL, AMOUNT	SELECTION FOR RESEARCH
Scopus	188	18
Scielo	18	4
Sciences	23	1
IOPScience	16	1
BCRP	1	1
TOTAL	245	25

The prism methodology was applied for systematic reviews.

Relevant journals were included for the development of the study, which addressed research published in the last 5 years between 2020 and 2024, obtaining a total of 25 scientific articles in those years. (Figure 3)

The collection of research from scientific journals such as Scopus, Scielo, Sciences and IOPScience, using search terms related to inclusion and exclusion criteria, used the PICO methodology as shown in Table 3, to select relevant studies, which should address the Mumford-Shah function and image segmentation.

Table 3 PICO shows the major aspects of the investigation in accordance to the PICO model. The Population is the cocoa that has to be analysed. The Intervention is the implementation of the Mumford-Shah functional algorithm of image segmentation, with the view of enhancing cocoa quality classification. Though, no explicit comparison group is stated, the study is concerned with the efficacy of the algorithm. The Determination and classification of cocoa quality is the Outcome that is determined using the results of the segmentation.

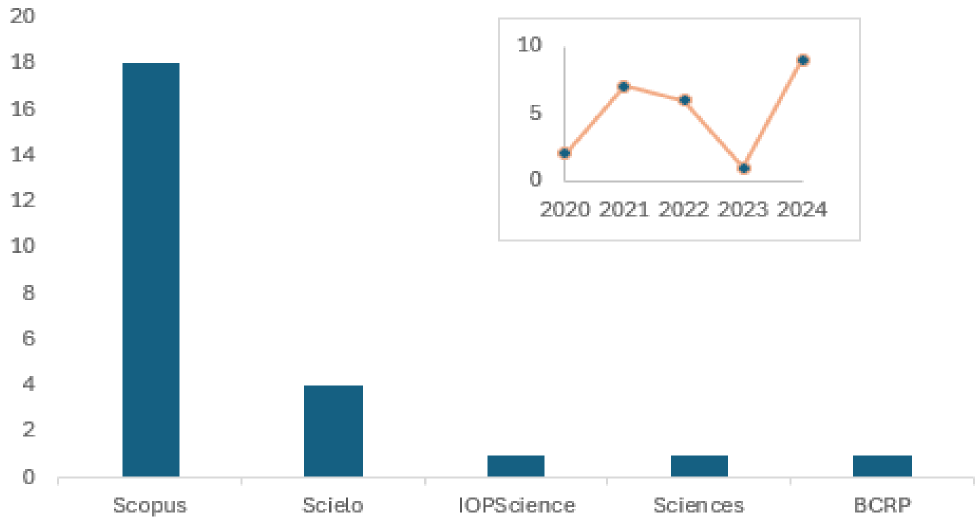


Figure 3. Information resource according to journals used

Table 3. Table PICO

Population	**Intervention**	**Results**
Cocoa	Mumford-Shah	Functional Algorithm
	Image segmentation	Quality

METHODOLOGY

Mumford-Shah functional determination

The Mumford-Shah functional algorithm is not an emerging technology, as it was developed in 1989 by David Mumford and Jayant Shah, however, it is still relevant and has emerging technological applications such as computer vision and deep learning.

In this context, thanks to technological advances and the functionality of mathematical algorithms, it was proposed to analyze the Mumford-Shah functional model and image segmentation to improve the identification of quality cocoa [8].

As shown in the following Mumford-Shah equation 1 for image segmentation:

$$E(f,r) = v \int_{\Omega\backslash r}(f-g)^2 + \lambda \int_{\Omega\backslash r}|\nabla f|^2 + \mu|r| \quad (1)$$

Table 4. Data table

Mumford-Shah image segmentation equation	
Parameters	Description
λ, u	Represents the original image
C	Represents the set of edges in the image region
Length (C)	It is the length of the curve μ
a	Non-negative penalty parameters
	The larger a is, the softer the image will be
	The larger u is, the shorter the curve will be C
u	can approximate the data pair (u, C) and control the length of the surrounding curve
∇f	The gradient off, used to measure the variation in intensity of the segmented image within the region

The values are as follows: Ω is the image property, g is the image to be segmented, r is the union of the edges of each segmented region, f is the segmented image and $|r|$ is the total length of the arcs that comprise r. Finally, λ, μ and v are weights that allow improving the quality of the segmented image. With the Mumford-Shah function, the most precise edges of the image can be detected are shown in table 4 [9].

This algorithm works by consisting of three terms: Fidelity Term shown in equation 2 and 3 [6]

$$\int_{\Omega\backslash r} |\nabla f|^2 \quad \text{Softness level term} \tag{2}$$

$$\int_{\Omega\backslash r} ((f|r|)^{r})^2 \quad \text{Edge length term} \tag{3}$$

The study and application of this Mumford-Shah method, integrated with current technology, will benefit all fields of agricultural research, therefore, the main objective is to understand the functionality of this method applied to the cocoa industry.

It is very important to recognize what professionals attribute with respect to the demand for cocoa quality, if some time ago there was no law that required adequate quality for national and international markets, as of 2017 the technical standard NTP 208.040:2017 was approved, which establishes the quality and classification requirements for Peruvian cocoa.

The research seeks to answer the following question clearly and concisely:

¿How does the Mumford-Shah functional algorithm influence the combination with image segmentation to improve cocoa quality?

This question examines the influence of the Mumford-Shah algorithm on the quality assessment of cocoa and provides a comparative analysis of its effectiveness against conventional inspection methods.

Segmentation Process

The following Figure 4, 5 and 6 shows a segmentation obtained by applying the algorithm based on the Mumford-Shah functional, for the recognition and determination of the quality of cocoa, achieving a precise partition of the regions of interest.

Figure 4. Cocoa in the "Ripe" state

Figure 5. Cocoa in "unripe" state

Figure 6. Cocoa in a “sick” or “spoiled” state

Currently there are a number of methods for image recognition and segmentation [10]. Which can be used in different industrial sectors, from agriculture, security and medicine. However, there are many efficient methods such as the Mumford-Shah functional algorithm that are excellent for image segmentation and reconstruction [6].

For the development of this article, it was carried out based on the mixed review, which is a research approach that exhaustively and even-handedly tracks, collects, evaluates and synthesizes all existing evidence related to addressing the study objective "Determination of cocoa quality using the Mumford-Shah functional algorithm and image segmentation" using a programming language in Matlab [11].

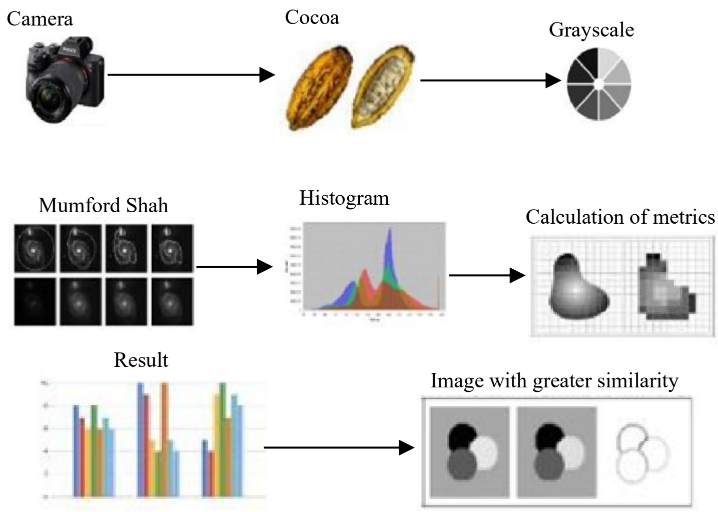


Figure 7. Cocoa quality classification pipeline: a visual overview

Figure 7 demonstrates that the process of quality categorization of cocoa is performed through the division of images. It commences with obtaining the image and then preprocesses it (conversion to grayscale), and characteristic extracted (histograms, graphs). The significant segmentation is by employing the Mumford-Shah functional to arrive at a proper segmentation. The segments are classified based upon characteristics like area, perimeter and eccentricity and majority on the ground in the segmented regions is the last consideration. It is an automated process of quality cocoa and efficiency in quality management and decision making.

Algorithm 1: Cocoa Quality Classification Using Mumford-Shah Functional Algorithm for Image Segmentation

Input

The input to the system is an image of cocoa at various stages (unripe, ripe, diseased), denoted as:

$$I(x, y) \in \mathbb{R}^{M \times N \times 3}$$

Step 1: Image Acquisition

Convert the color image to grayscale:

$$I_g(x,y) = 0.2989\, I_R + 0.5870\, I_G + 0.1140\, I_B$$

Step 2: Preprocessing

Apply a smoothing filter to reduce noise and simplify segmentation:

$$I_s(x,y) = I_g(x,y) * G_\sigma(x,y)$$

Step 3: Mumford-Shah Segmentation

The Mumford-Shah functional for image segmentation is defined as:

$$E(f,C) = \lambda \int_\Omega (f(x,y) - I_s(x,y))^2\, dx\, dy + \alpha \int_{\Omega\setminus C} |\nabla f(x,y)|^2\; dx\, dy + \mu\, \text{Length}(C)$$

where:

$f(x,y)$is the segmented image,

$C$is the set of edges (region boundaries),

$\nabla f$is the gradient of f,

$\lambda, \alpha, \mu$are weighting parameters for fidelity, smoothness, and edge detection.

Minimize the functional to find the optimal segmentation:

$$\left(f^*, C^*\right) = \arg \min_{f,C} E(f,C)$$

Step 4: Feature Extraction

For each segmented region R_i, extract the following features:

Area:

$$A_i = \sum_{(x,y)\in R_i} 1$$

Perimeter:

$$P_i = \sum_{(x,y)\in \partial R_i} 1$$

Eccentricity:

$$E_i = \sqrt{1 - \frac{\lambda_2}{\lambda_1}}$$

Step 5: Quality Classification

Cocoa is classified based on thresholds for area A, perimeter P, and eccentricity Eas follows:

$$Q(R_i) = \begin{cases} \text{Unripe,} & A_i > A_u, P_i > P_u, E_i < E_u \\ \text{Ripe,} & A_i \in [A_r^{min}, A_r^{max}], P_i \in [P_r^{min}, P_r^{max}], E_i \in [E_r^{min}, E_r^{max}] \\ \text{Diseased,} & A_i < A_d, P_i < P_d, E_i > E_d \end{cases}$$

Step 6: Final Decision

The overall cocoa quality is determined by the majority vote across all segmented regions:

$$Q_{\text{final}} = \text{mode}\{Q(R_1), Q(R_2), \ldots, Q(R_n)\}$$

Output

The output is the final cocoa quality classification:

$$Q_{\text{final}} \in \{\text{Unripe,Ripe,Diseased}\}$$

This decision is based on the majority classification of the segmented regions within the cocoa image.

Algorithm 1 is an automatic determination of the quality of cocoa with the Mumford-Shah functional image segmentation. It turns cocoa images into grayscale, smoothes the image and breaks the image according to edge locating and smoothness. The area, perimeter and eccentricity are some of the key features that are extracted to classify the cocoa into unripe, ripe, or diseased. The last categorization is registered by the majority vote of the segmented regions and is an efficient, objective and automated process of quality control and decision making.

RESULTS AND DISCUSSION

Mumford-Shah equation to improve image segmentation performance currently is as follows equation 4 and table 5 and 6 [12]

$$E(u, C) = \lambda \int_{\Omega}(u_q - u)^2 dxdy + a \int_{\Omega\backslash c}|\nabla u|^2 \, dxdy + \mu length(C) \quad (4)$$

Table 5. Data table

Mumford-Shah image segmentation equation	
Parameters	Description
λ, u	Represents the original image
C	Represents the set of edges in the image region
Length (C)	It is the length of the curve μ
a	Non-negative penalty parameters
	The larger a is, the softer the image will be
	The larger u is, the shorter the curve will be C
u	can approximate the data pair (u, C) and control the length of the surrounding curve
∇f	The gradient of f, used to measure the variation in intensity of the segmented image within the region

The Mumford-Shah functional algorithm is focused on solving the image segmentation problem of a classical procedure, finding optimal segment results, the original Mumford-Shah function is the following equation 5, 6 and 7 [9].

$$E(u, C) = \lambda \int_{\Omega}(U_0 - U)^2 \, dxdy + a \int_{\Omega/c}|\nabla u|^2 dxdy + \mu length(C) \quad (5)$$

$$E(u, C) = \lambda \quad (6)$$

$$F^{MS}(\mu, C) = \mu.length(C) + \lambda_1 \int_{\Omega}|u_0 \quad (x, y) - u(x, y|^2 \, dxdy + \lambda_1 \int_{\Omega}|u_0(x, y) - u(x, y|^2 \, dxdy \quad (7)$$

The study carried out with the Mumford-Shah logarithm using Matlab software allowed finding homogeneity in the segmented images to improve the selection of quality cocoa, using the deep learning tool [13] [14].

Table 6. Data table

Mumford-Shah Functional Algorithm	
Parameters	**Description**
C	Curve in the level set method
	μ ≥ 0, ν ≥ 0, λ1, λ2 > 0
Length (C)	It is the length of the curve C

The Figures 8, 9, and 10 show the quality analysis process of cocoa: the original image (a) is used to observe the seeds in their initial state; the conversion to grayscale (b) eliminates color information to simplify the analysis; the smoothed image (c) reduces noise, facilitating accurate segmentation; and the segmentation result (d) delimits the regions of interest (seeds) with respect to the background. The complementary numerical analysis, with metrics such as areas, perimeters and eccentricity, allows to evaluate uniformity and detect possible defects in the seeds, offering an objective evaluation of their quality.

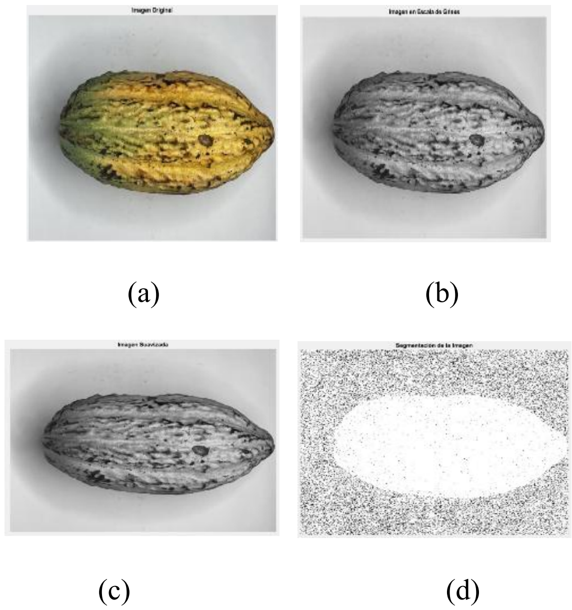


Figure 8. Cocoa quality analysis: number of regions: 768, average areas: 13997.49 pixels, average perimeters: 24.57 pixels, average eccentricity: 0.21

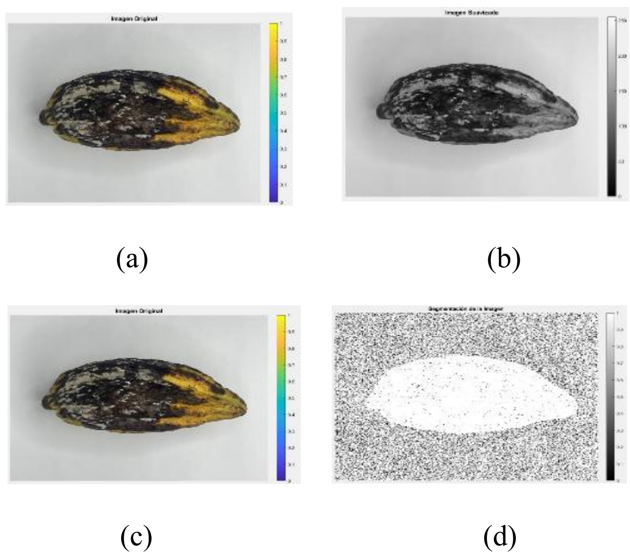
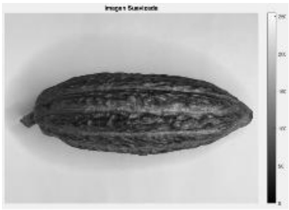
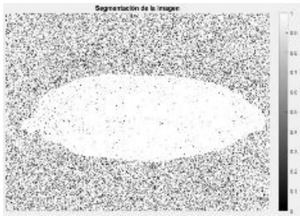


Figure 9. Cocoa quality analysis (image of diseased cocoa): number of regions: 1705, average areas: 5936.61 pixels, average perimeters: 11.68 pixels, average eccentricity: 0.21


(a) (b)

(c) (d)

Figure 10. Cocoa quality analysis (green unripe cocoa image): number of regions: 997, average areas:10509.80 pixels, average perimeters: 18.40 pixels, average eccentricity: 0.20

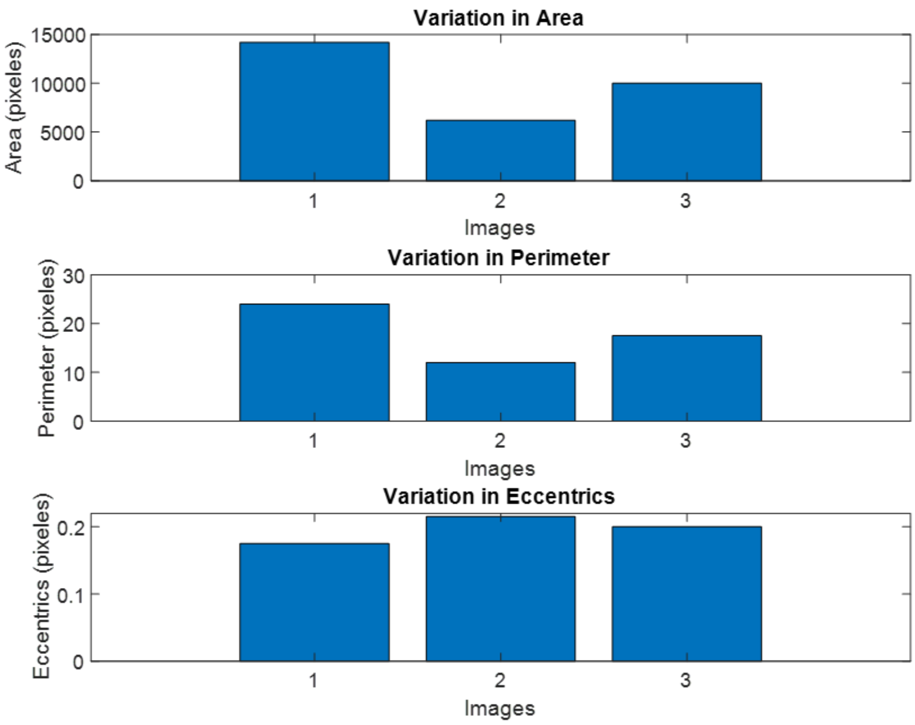


Figure 11. Metric comparison chart

Figure 11 compares the variation in quality metrics between images, helping to identify significant differences in the characteristics of cocoa beans. Three standard images were created and trained to then analyze it and verify whether it compares the images of sick and green cocoa with the standard images.

Table 7. Pattern data comparison table

	Pattern 1	**Pattern 2**	**Pattern 3**
Area	13141.06	39941.17	33364.23
Perimeter	22.54	22.54	49.16
Eccentrics	0.21	0.20	0.20

Average Pattern Metrics:

- Average Area: 28815.49
- Average Perimeter: 43.59
- Average Eccentricity: 0.20

Table 8. Image results comparison table

	Image 1	Image 2	Image 3
Area	9527.49	6181.90	9302.46
Perimeter	16.78	12.31	16.98
Eccentrics	0.20	0.22	0.20
Total Distance	6438.27	7554.96	6513.22
Quality	Not Optimal	Not Optimal	Not Optimal

Variation analysis: In addition to color analysis, the implemented program evaluates variations in shape characteristics, such as area, perimeter and eccentricity of the segmented regions shown in table 7 and 8. These metrics allow detecting differences in size, shape or uniformity between the standard images and those to be compared. The generated graphics help to observe how these metrics vary between images, which is crucial for a complete analysis. The following 3 standard images determine (Figures 12, 13, and 14): the analysis of each image is taken to grayscale and segmented, adding the generation of its color histogram for each image [15].

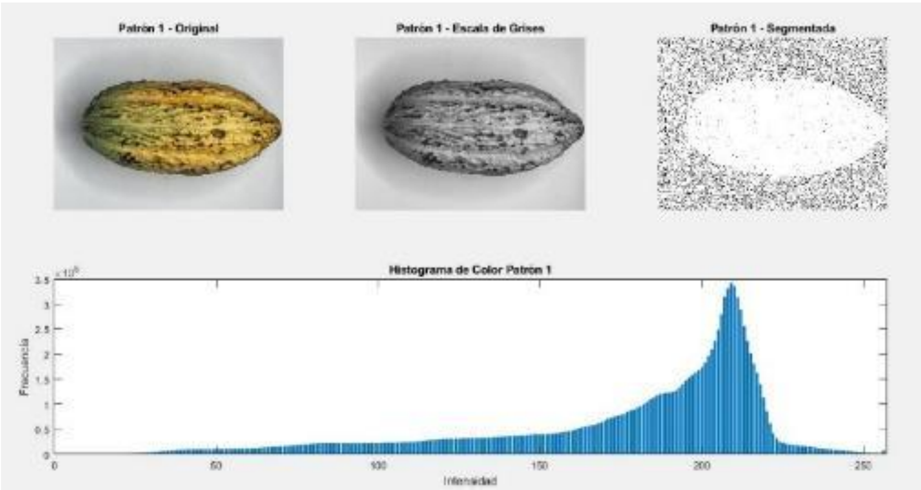


Figure 12. Pattern graph 1

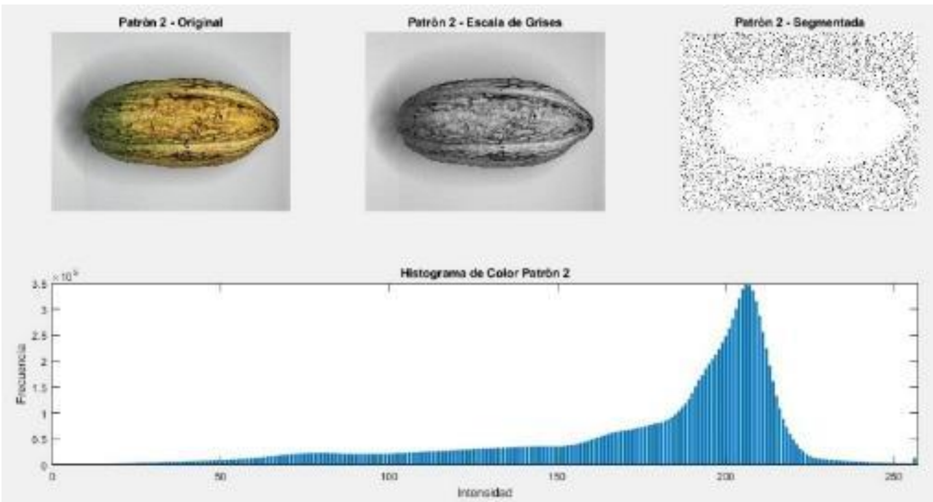


Figure 13. Pattern graph 2

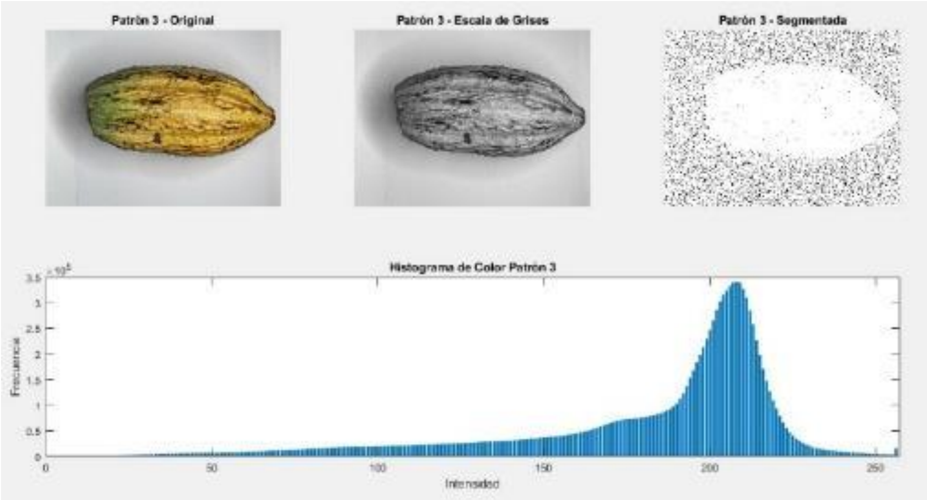


Figure 14. Pattern graph 3

Comparison

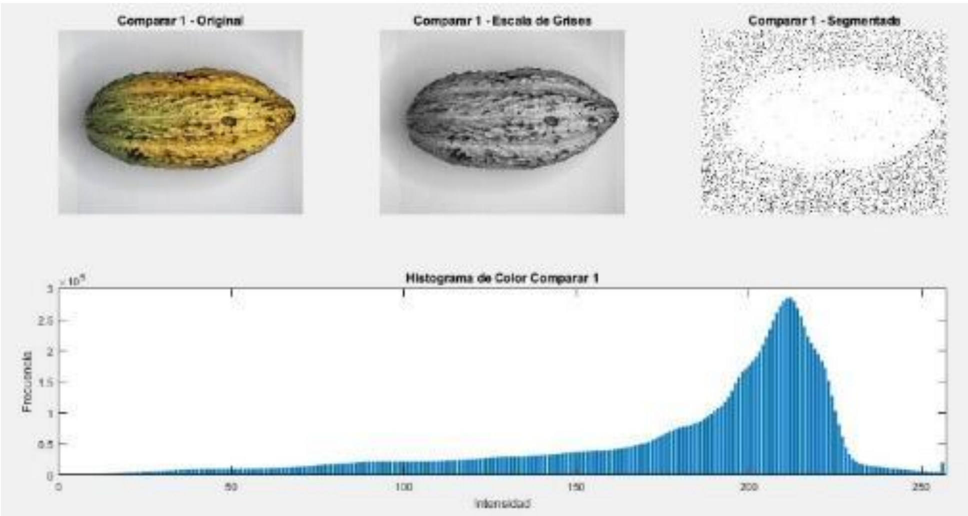


Figure 15. Pattern graph 1

First image (Figure 15) of comparison with the patterns, in which it is verified that it complies with the similarity.

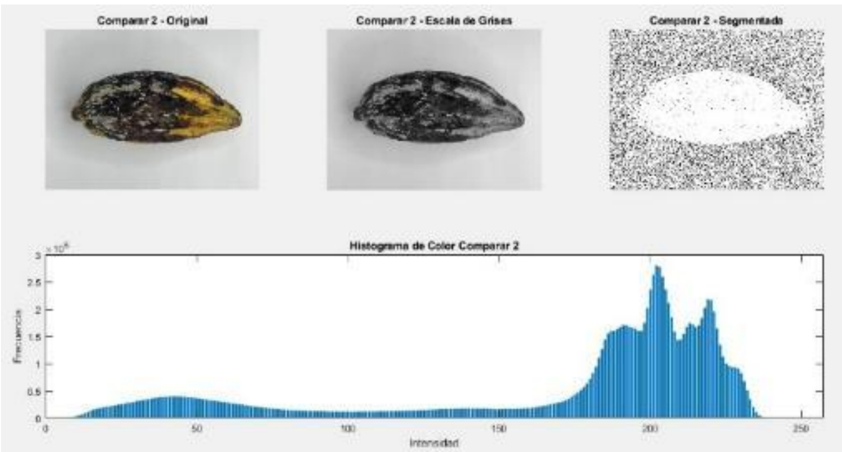


Figure 16. Pattern graph 2

Comparison image (Figure 16), but it is of a sick cocoa in which the comparison of color and segmentation is evident that "does not comply" with the similarity, therefore the recognition is "negative".

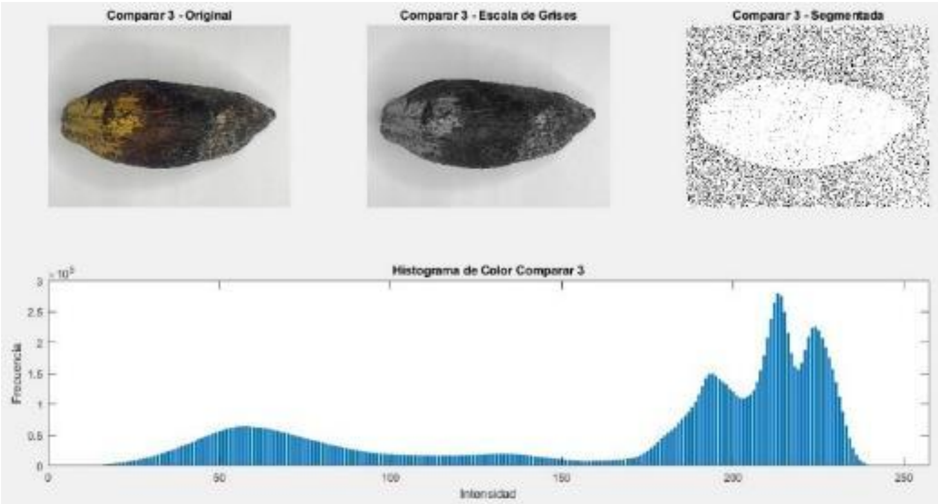


Figure 17. Pattern graph 3

This third image (Figure 17) shows a comparison equal to the previous one, it shows an image of a sick cocoa which "does not comply" with the characteristics of similarity with respect to the pattern.

A summary about each image shown: The analysis of the standard and comparison images begins with a detailed visualization of each processed image. For the standard images, the original image is first shown, which includes details of texture, color and possible defects of the cocoa. Afterwards, a grayscale image is generated, which simplifies the analysis by removing the color information, facilitating segmentation. The segmented image is the result of the functional Mumford-Shah algorithm, where regions of interest, such as cocoa seeds, are highlighted. Finally, a color histogram illustrates the distribution of red channel intensities, providing a key tool for analyzing the chromatic composition of the images [16].

For the images to be compared, the same steps are performed. This allows to observe how these candidate images behave during the segmentation process and how their color distribution compares to the pattern images. These visualizations are essential to understand the similarities and differences in shape and color between the images as shown [17].

The model implemented in Matlab evaluates the similarity between the target images and the images to be compared by calculating absolute differences in their color histograms. For each target image, the image to be compared with the smallest color difference is identified, indicating the highest chromatic similarity. The results are presented numerically in the console, highlighting which candidate image is most similar to each target and what the magnitude of the difference is [18].

For example, if the model indicates that "Pattern 1 is most similar to Compare 2 with a color difference of 150.34", this means that, of all the images to compare, image 2 has the closest color composition to Pattern 1, with this difference being quantified in intensity units (Figure 18).

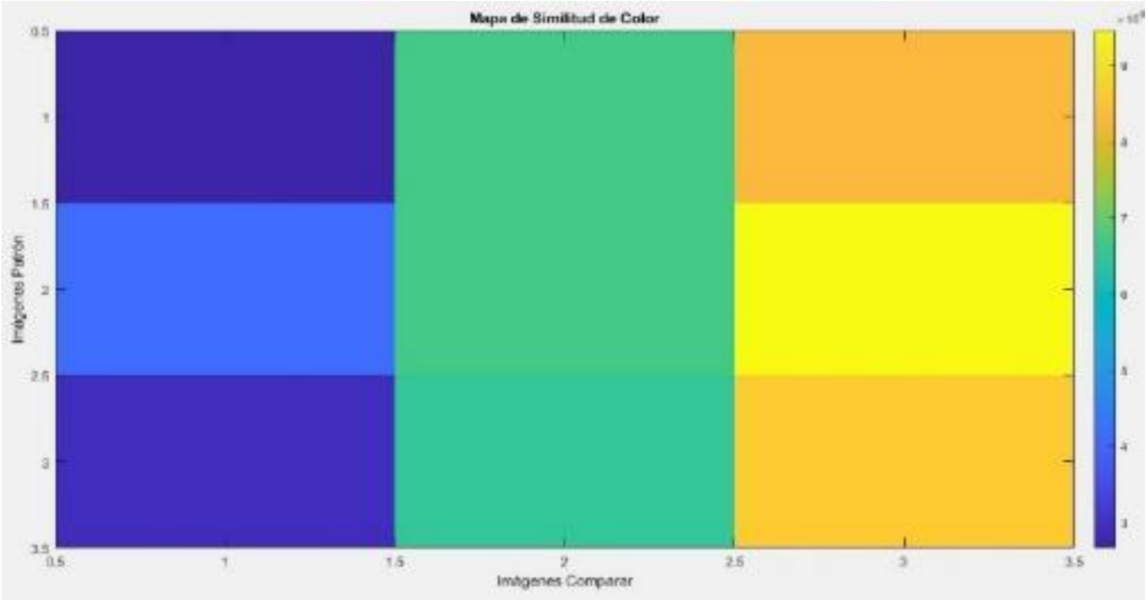


Figure 18. Color similarity map of the analyzed images

Image similarity by color:

Pattern 1 is most similar to compare 1 (Color difference: 2671110.00).

Pattern 2 is most similar to compare 1 (Color difference: 4178846.00).

Pattern 3 is most similar to compare 1 (Color difference: 2884940.00).

Figure 18 shows the color similarities between all the benchmark and comparison images. In this map, the X-axis represents the comparison images and the Y-axis represents the benchmark images. Dark colors in the map indicate less color difference, reflecting greater similarity between the images, while light colors indicate greater difference. This map allows you to visually identify which images have similar color patterns, making it easier to analyze large data sets.

The implemented model combines visual and numerical analysis to identify the images to be compared that are most similar to the standard images in terms of color and shape. Charts such as color histograms and similarity maps provide a clear visual representation, while numerical values quantify the differences and support objective selection [19] [20]. This analysis allows for informed decisions, such as identifying cocoa images that meet the standards set in the standard images, improving processes such as quality control and cocoa classification.

CONCLUSION

The given research proves that the Mumford-Shah functional algorithm is efficient in the context of cocoa image segmentation to determine the quality, provides more objective classification as compared to the traditional sensorial methods. The most notable results are that the algorithm was able to distinguish between unripe, ripe and diseased cocoa, with the unripe cocoa giving 997 segments and an average area of 10,509.80 pixels, ripe cocoa giving 768 segments and an average area of 13,997.49 pixels and diseased cocoa giving 1,705 segments and an average area of 5,936.61 pixels. All these findings indicate that the algorithm can be used to help classify the quality of cocoa, cut losses due to post-harvest, and perform quality control. Nonetheless, the research has certain weaknesses. A small set of cocoa images was used to test the model, and this might not be representative enough of the variations that crop up in the agricultural settings. Also, the performance of the algorithm in the poor conditions, including different light and moisture, was not tested. Besides, Mumford-Shah algorithm is effective, but computationally intensive and will need to be optimized to be used in large-scale and real time application.

The next generation of research must be done to enhance the computational efficiency of the MumfordShah algorithm, potentially using parallel processing, or incorporating deep learning to accelerate processing. It would be better to make the data more diverse and increase the number of different environmental factors to present a more comprehensive assessment of the relevance of the algorithm. Besides, the scalability and accuracy of cocoa quality determination systems may be further improved by integrating the Mumford-Shah algorithm with automated harvesting systems to evaluate quality in real-time and fish into deep learning-based segmentation models.

REFERENCES

[1] Arévalo-Hernández CO, Arévalo-Gardini E, Farfan A, Amaringo-Gomez M, Daymond A, Zhang D, Baligar VC. Growth and nutritional responses of juvenile wild and domesticated cacao genotypes to soil acidity. Agronomy. 2022 Dec 9;12(12):3124. https://doi.org/10.3390/agronomy12123124

[2] Rasgado Bonilla GN, Renard Hubert MC. El dilema de la calidad: valorización del cacao del Soconusco, Chiapas, México. RIVAR (Santiago). 2022 May;9(27):22-38. http://dx.doi.org/10.35588/rivar.v9i27.5624

[3] Rossini R, Vega M, Quispe Z, Pérez F. Banco Central de Reserva del Perú.

[4] Heredia Gómez JF, Rueda Gómez JP, Talero Sarmiento LH, Ramírez Acuña JS, Coronado Silva RA. Determinación de la madurez de mazorcas de Cacao, haciendo uso de redes neuronales convolucionales en un sistema embebido.

[5] Romero Vergel AP, Camargo Rodriguez AV, Ramirez OD, Arenas Velilla PA, Gallego AM. A crop modelling strategy to improve cacao quality and productivity. Plants. 2022 Jan 7;11(2):157. https://doi.org/10.3390/plants11020157

[6] Kang X, Hua C. Multilevel thresholding image segmentation algorithm based on Mumford–Shah model. Journal of Intelligent Systems. 2023 Nov 28;32(1):20220290. https://doi.org/10.1515/jisys-2022-0290

[7] Dwivedi V, Srinivasan B, Krishnamurthi G. Physics informed contour selection for rapid image segmentation. Scientific Reports. 2024 Mar 24;14(1):6996. https://doi.org/10.1038/s41598-024-57281-x

[8] Moll S, Pallardó-Julià V, Solera M. Segmentation in Measure Spaces. Applied Mathematics & Optimization. 2024 Jun;89(3):66. https://doi.org/10.1007/s00245-024-10134-5

[9] Choi HT, Hong BW. Unsupervised Object Segmentation Based on Bi-Partitioning Image Model Integrated with Classification. Electronics. 2021 Sep 18;10(18):2296. https://doi.org/10.3390/electronics10182296

[10] Zúñiga Picado LA, Campos Boza S, Mora Chaves JR, Barboza-Barquero L. Quantification of the percentage of total broken grain in rice (Oryza sativa L.) by digital image analysis. Agronomía Mesoamericana. 2022 Dec;33(spe1). https://doi.org/10.15517/am.v33iEspecial.51568

[11] Kiefer L, Storath M, Weinmann A. PALMS image partitioning-a new parallel algorithm for the piecewise affine-linear mumford-shah model. Image Processing On Line. 2020 Sep 29;10:124-49. https://doi.org/10.5201/ipol.2020.295

[12] Case N, Vitti A. Reconstruction of multi-temporal satellite imagery by coupling variational segmentation and radiometric analysis. ISPRS International Journal of Geo-Information. 2021 Jan 6;10(1):17. https://doi.org/10.3390/ijgi10010017

[13] Fong Amaris WM, Suárez DR, Cortés-Cortés LJ, Martinez C. CAM: a novel aid system to analyse the coloration quality of thick blood smears using image processing and machine learning techniques. Malaria Journal. 2024 Oct 7;23(1):299. https://doi.org/10.1186/s12936-024-05025-7

[14] Shah N, Patel D, Fränti P. Image segmentation by pairwise nearest neighbor using Mumford-Shah model. Proceedings of CECNet 2021. 2021. http://dx.doi.org/10.3233/FAIA210465

[15] Bernal-Catalán E, Cruz-Gámez E, Montero-Valverde JA, Hernández Reyna R, Hernandez-Hernández JL. Detection of Exudates and Microaneurysms in the Retina by Segmentation in Fundus Images. Revista mexicana de ingeniería biomédica. 2021 Aug;42(2). https://doi.org/10.17488/rmib.42.2.6

[16] Horenko I, Pospíšil L, Vecchi E, Albrecht S, Gerber A, Rehbock B, Stroh A, Gerber S. Low-cost probabilistic 3D denoising with applications for ultra-low-radiation computed tomography. Journal of Imaging. 2022 May 31;8(6):156. https://doi.org/10.3390/jimaging8060156

[17] Cao J, Chen K, Han H. A fractional-order image segmentation model with application to low-contrast and piecewise smooth images. Computers & Mathematics with Applications. 2024 Jan 1;153:159-71. https://doi.org/10.1016/j.camwa.2023.11.010

[18] Huang T, Yin H, Huang X. Improved genetic algorithm for multi-threshold optimization in digital pathology image segmentation. Scientific Reports. 2024 Sep 28;14(1):22454. https://doi.org/10.1038/s41598-024-73335-6

[19] Felicetti A, Paolanti M, Zingaretti P, Pierdicca R, Malinverni ES. Mo. Se.: Mosaic image segmentation based on deep cascading learning. Virtual Archaeology Review. 2021 Jan 19;12(24):25-38. https://doi.org/10.4995/var.2021.14179

[20] Shah N, Patel D, Fränti P. k-Means image segmentation using Mumford–Shah model. Journal of Electronic Imaging. 2021 Nov 1;30(6):063029-. https://doi.org/10.1117/1.JEI.30.6.063029

[21] Xiao X, Wen Y, Chan R, Zeng T. Image Segmentation Using Bayesian Inference for Convex Variant Mumford–Shah Variational Model. SIAM Journal on Imaging Sciences. 2024 Mar 31;17(1):248-72. https://doi.org/10.1137/23M1545379

[22] Burrows L, Theljani A, Chen K. On a variational and convex model of the Blake–Zisserman type for segmentation of low-contrast and piecewise smooth images. Journal of Imaging. 2021 Oct 28;7(11):228. https://doi.org/10.3390/jimaging7110228

[23] Sucipto, Wulandari S, Ariani I. Quality risk analysis of cocoa agroindustry: a case study in Pesawaran District, Lampung Province. In IOP Conference Series: Earth and Environmental Science 2021 Nov (Vol. 892, No. 1, p. 012058). IOP Publishing. https://doi.org/10.1088/1755-1315/892/1/012058

[24] Salazar E, Valenzuela R, Aguilar M, Aranda N, Sotelo A, Chire G, Ureña M. Physicochemical properties and microbial group behavior of postharvest peruvian cocoa bean (Theobroma cacao L.). Enfoque Ute. 2020 Dec;11(4):48-56.