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Study of the microstructure-property-processing relationship in five potato (*Solanum tuberosum*) varieties during the frying process based on an automatic classification system using convolutional neural networks

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Abstract

Our objective was to identify and analyze the microstructural features of five different Peruvian potato varieties in fresh material and a frying process, using a 3^2-factorial arrangement of temperature and time. Two types of characteristics were measured. The first ones were of microstructural type (i.e., area, perimeter, length of major axis, length of minor axis, roundness, elongation, and compactness) and the second ones were of physicochemical type (i.e., L^*, a^*, b^*, ΔE, acrylamide concentration, fat percentage, moisture percentage, and texture). For this purpose, potato microstructural characterization software was implemented, developing algorithms for image processing and analysis, as well as the classification of structural characteristics. Potato variety was found to exert a significant effect on the microstructural parameters of area, perimeter, major axis length, minor axis length, roundness, and compactness, followed by time, with a significant effect on the microstructural parameters of area, perimeter, major axis length, minor axis length, and compactness. Temperature exerts a significant effect only on roundness and elongation parameters. To observe the relationship between the microstructural and physicochemical parameters, a Pearson correlation was used where it was observed that the correlations between the physicochemical and microstructural variables evaluated were medium to strong.

Keywords: microstructural; Peruvian potato varieties; frying process; image processing; microstructure-property-processing relationship.

Practical application: This research proposes to contribute to the knowledge and interpretation of the structure-property-process relationships of plant tissues in potato varieties, which together with an artificial intelligence system can discriminate much better the micrographs used. Microscopy image analysis has become more reliable in understanding the structure and composition properties of plant cells and tissue. It can be utilized for product development, manufacturing process, and the detection of foreign materials to further ensure product quality and safety.

1 INTRODUCTION

Food properties depend on their structure and the changes generated by processing. However, it is impossible to predict the alterations that a food undergoes along the production chain, especially if we do not know how the properties and structure of a food are related. Therefore, it is necessary to develop models for predicting such behaviors along the production processes. In this aspect, models have been developed using micrographs (Castro et al., 2019; Derossi et al., 2017; Karim et al., 2018), where the methodology to observe and analyze the microstructure is still in the development stages.

These new methodologies must be able to predict changes in food properties because they use simplified relationships and do not consider the effect of the processing on the structure and the macroscopic properties.

The potato (*Solanum tuberosum L.*) belongs to the Solanaceae family and can be classified according to color and shape. Potatoes are rich in carbohydrates and several micronutrients such as vitamin C, vitamin B1, vitamin B3, iron, and minerals such as potassium, phosphorus, and magnesium. Potatoes are also rich in dietary antioxidants, which play a vital role in disease prevention. However, potatoes also contain toxic compounds, namely, glycoalkaloids, which cause gastrointestinal disorders (Sharma et al., 2020). Potato is the third most important food crop worldwide, with an average annual production of 356 million tons during the past decade, and is believed to contribute significantly to maintaining global food security (Grados et al., 2020). The internal quality is determined by the chemical composition of the potato, which is one of the most used factors for the classification and purchase of varieties for the elaboration of different potato products (de Haan & Rodriguez, 2016).

Food microstructure is understood as the spatial arrangement of identifiable elements in food and their interactions at levels below 100 µm (Aguilera, 2005; Sharma et al., 2020). The microstructure of potato flesh and the properties of cell wall

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polymers (i.e., size of parenchyma cells and nature of pectic materials) are two important factors that can influence the deformation occurring during chewing or mechanical processing (Bordoloi et al., 2012; Guedes et al., 2021). Microstructural features of raw potatoes, such as parenchyma cell size, cell wall composition, and thickness, have been reported to impact the final texture significantly (Bordoloi et al., 2012).

Potato tissue consists of large (200 × 340 μm) and small (80 × 90 μm) cells, and each cell was observed to contain 6-10 large starch granules (10-70 μm in diameter) and hundreds of very small starch granules (0.5-1.0 μm). In addition, the tubers are reported to have an isodiametric polyhedral shape, varying in cell size, cell shape, cell wall thickness, and starch granule size among varieties (Singh et al., 2005).

The main changes occurring when potatoes are fried are that the high temperature and water inside the cells influence starch gelatinization. Research using confocal laser scanning microscopy to section the potato rind after frying revealed that frying oil was inside, in pockets, or around intact potato cells (Bouchon & Aguilera, 2001; Pedreschi et al., 2016). Microscopy techniques are valuable for examining the changes in potato microstructure and starch gelatinization *in situ*. However, no standardized quantitative method has been developed to measure such changes, which would be useful for assessing these changes when using different potato frying technologies concerning digestibility.

The structure-property set refers to the knowledge of the structure and properties of a system, as well as the understanding of the existing relationships between both concepts and, of course, the capacity to predict the changes that occur in the properties of food when any change in its structure occurs (Aguilera et al., 2003).

This research is concerned with structure-property-processing relationships in potatoes and will describe, through predictive mathematical analysis, how microstructure influences the physicochemical properties of French fries and how it can be demonstrated that most macroscopic properties are correlated with microscopic characteristics. From the theoretical point of view, experimental evidence will be generated, such as the analysis of structures in plant tissues for the characterization of the structural elements of the tissue (cells and intercellular spaces).

2 MATERIALS AND METHODS

2.1 Unit of analysis, population, and study sample

The unit of analysis is the product harvested and selected according to the following criteria: fresh, recently harvested product of the industrial biotypes. All samples at harvesting showed no external damage and were stored at a temperature of 15°C with an average relative humidity of 80%. The varieties selected for this research are Peruvian and belong to the following varieties: Unica, Libertena, Yungay, Amarilis, and Huevo de Indio (native).

From each of the five varieties, 3 kg per sample was selected for processing in frying and the generation of optical micrographs, as well as the measurement of physicochemical characteristics. The procedure was carried out in triplicate. In addition, the five varieties were characterized, and the results are shown in Table 1.

2.2 Frying process

Raw potatoes were washed, peeled, and then cut into strips (10 × 10 × 40 mm) using a square cutter mold. Samples were immersed for 1 min in distilled water to remove occluded starch adhering to the surface. Adsorbent papers were used to drain excess water on the surface of the potato slices.

The frying process was carried out in a stainless-steel electric fryer. This equipment has a capacity of 3 L of oil and allows temperature control. The oil used was sunflower oil. Ten potato strips were placed in the center of the fryer to obtain uniform samples. The potatoes were fried at three different temperatures (170, 180, and 190°C) at three different times (1, 2.5, and 4 min). A portion of the oil was stored before and after the frying process for later analysis. The French fries were placed on absorbent paper to drain excess oil and cooled to room temperature before analysis. Each frying experiment was performed with fresh oil.

An arrangement was made for each frying treatment using a response surface central composite design, which will allow taking the data for the microstructural parameters and, at the same time, observing the simple effects concerning the output variables.

Table 1. Characterization of potato varieties.

Characteristics	Unit	'Huevo de Indio' Variety	'Yungay' Variety	'Liberteña' Variety	'Unica' Variety	'Amarilis' Variety
Carbohydrates	%	25	20	21	16	15
Ash	g/100 g	0.97	1.05	0.839	0.803	0.705
Total fat	%	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Moisture	%	67.1	79	78.5	82.9	84.1
Protein	%	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Total solids	%	24.65	21.83	22.5	27.37	24.08
Specific gravity	%	1.095	1.089	1.108	1.105	1.11
Starch	%	19.2	20.1	20.4	18.9	19.5
Reducing sugars	%	0.5	0.35	0.31	0.41	0.51
Nutritional value	kcal/100 g	99.7	79.6	82.4	65.2	60.8

2.3 Obtaining micrographs under an optical microscope

A section (1 × 0.5 × 0.5 cm) was cut from the French fry sample and sectioned with a vibratome (Leica VT1000S); the sections were 10 μm. All the samples were transferred to microscopic slides coated with 0.01% poly-L-lysine solution, and a drop of 5% toluidine blue dye was added.

2.4 Implementation and microstructural characterization of potatoes

The previously treated samples will be characterized by obtaining the statistical distribution of the size and shape parameters of each of the structural elements of the plant tissue under study. An automated system was developed based on Castro's proposal to obtain information on each element and to individualize them (Castro et al., 2019). The system was implemented in the mathematical software MATLAB 2019a. The work scheme developed is shown in Figure 1. The determined morphological parameters are summarized in Figure 2 and were area (A), length of major axis (L), length of minor axis (l), perimeter (P), roundness (R), elongation (E), and compactness (C).

2.5 Color analysis

The color of French fries was determined using a Chroma meter (CM-2003d, Konica Minolta, Japan). The spectrophotometer was calibrated with a standard whiteboard before testing. The scale was displayed in L^* (0 = black; 100 = white), a^* ($-a$ = green; $+a$ = red), and b^* ($-b$ = blue; $+b$ = yellow). Color measurements were made at 10 locations on the surface of each sample. Overall color differences (ΔE) were calculated as Equation 1:

$$\Delta E = \sqrt{(L* - L*_0)^2 + (a* - a*_0)^2 + (b* - b*_0)^2} \quad (1)$$

2.6 Texture

The texture of French fries was evaluated with the puncture test using the Brookfield Texture Analyzer (TA-CT3 Texture Technologies Corporation, Scarsdale, NY, USA). The firmness of the raw potato slices was defined as the maximum penetration force. The potato strip was placed in the middle of a hollow fixture plate and penetrated with a cone-shaped probe at a 30° angle (TA-17) (Zheng & Moreira, 2020).

2.7 fat determination

The amount of fat in the analyzed flakes was determined by applying the AOAC Soxhlet procedure (Rani & Chauhan, 1995). Portions of 5 g of the French fry samples were extracted for 180 min using diethyl ether as solvent (150 mL/sample). The procedure was repeated three times for each sample, and a final result was calculated as the mean value of the data obtained. The oil content was expressed in g/g dry basis of potato strips.

2.8 Moisture determination

The moisture content of the samples was determined according to the AOAC method 964.22. About 4 g of samples were crushed and dried in an oven (POL-EKO) at 105 ± 2°C until a constant weight was reached. Moisture content was presented as g/g wet basis of potato strips.

2.9 Acrylamide determination

The liquid chromatography-mass spectrometry (LC/MS--MS) method was used to determine acrylamide in French fry strips, and the unit of reading is μg/kg.

2.10 Data processing and analysis techniques

The data were analyzed through a multifactorial ANOVA with a response surface model fitting to compare the data for each type of variety and to see the simple effects on each variable. A correlation between microstructural and physicochemical parameters was also performed using Pearson's coefficient.

3 RESULTS

3.1 Microstructural features of potato varieties

Figure 2 shows the image processing that involved the recognition and interpretation of image features, which generated operations to identify objects by classifying them into different categories. The designed classifier followed supervised training, and it was possible to implement the classification algorithms by direct comparison of the measured features. This methodology has already been used with reference threshold values (Kraus et al., 2016).

The main problem with segmentation in food analysis is that the microstructure of food is inherently complex and difficult to automatically segment due to the large variation of shades of gray usually found in the images (Parada & Aguilera, 2007). The software used improved this aspect in the French fry samples, as seen in Figure 3.

As shown in Figure 3, automatic processing also has the advantage that measurements are faster if there are many images to analyze. Manual segmentation, performed in image analysis for food structure, is slower and subject to strong biases that depend on the human observer. Automatic methods, without much human interaction, are more suitable for producing quantitative data without introducing biases.

Determining the statistical distribution of the microstructural data is important in such a large sample of potato cells. Figure 4 shows the histograms of the parameters of compactness, elongation, roundness, length of the major axis, length of the minor axis, perimeter, and cell areas for the values of the French fries for the five varieties studied. It can be observed that the size and shape of the curves are similar for all parameters and all varieties. However, there is a shift of the curves corresponding to the elongation and roundness parameters, decreasing their values. This change can be attributed to the "cutting effect" produced in the preparation of the samples. The results for both types of parameters are similar to those obtained in other studies for other vegetables (Mayor et al., 2011; Reinheimer, 2012).

Figure 5 shows the comparison of the microstructural parameters of the five potato varieties. For this analysis, a multiple

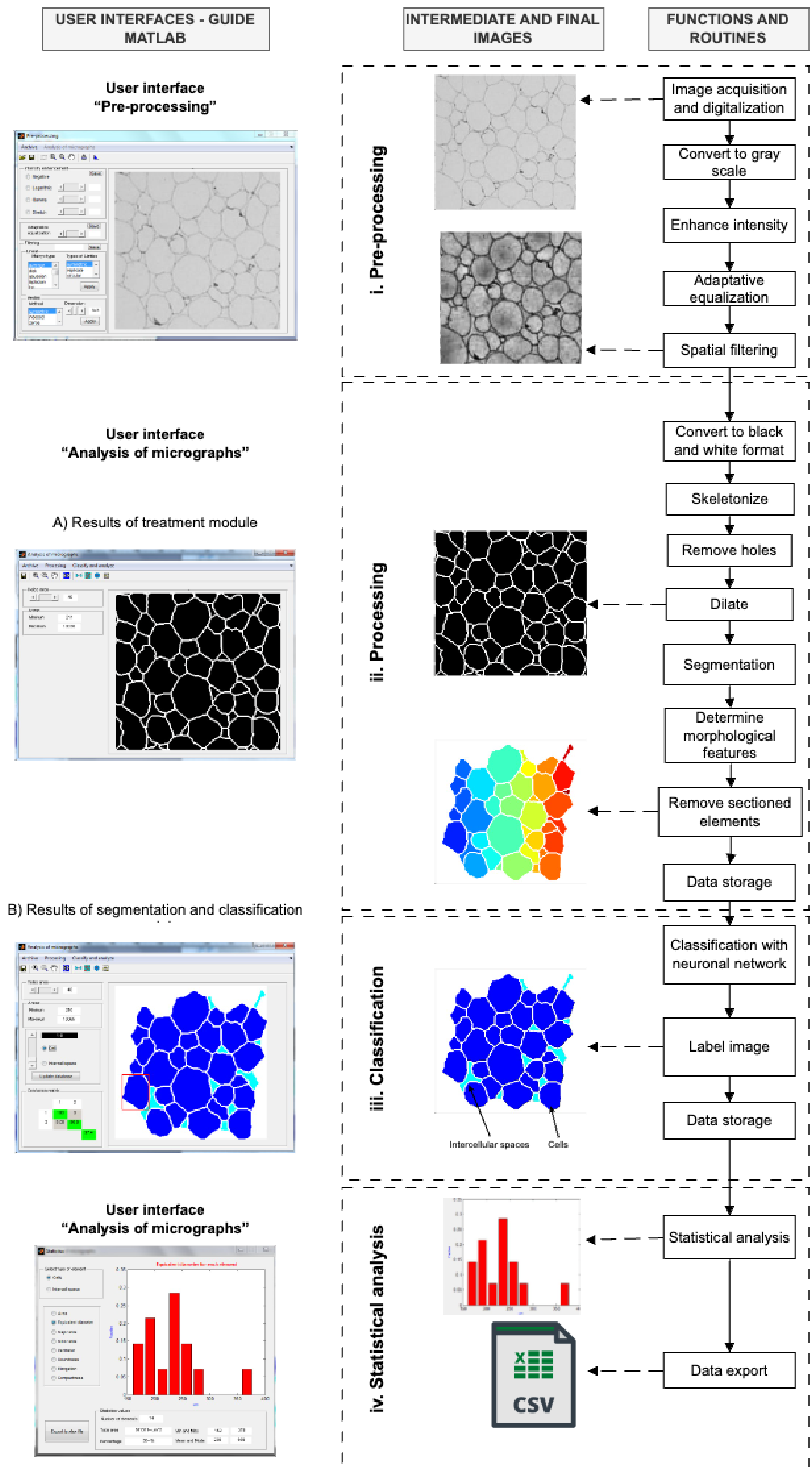

Figure 1. A general outline of the application: modules and routines, most important functions, and guides.

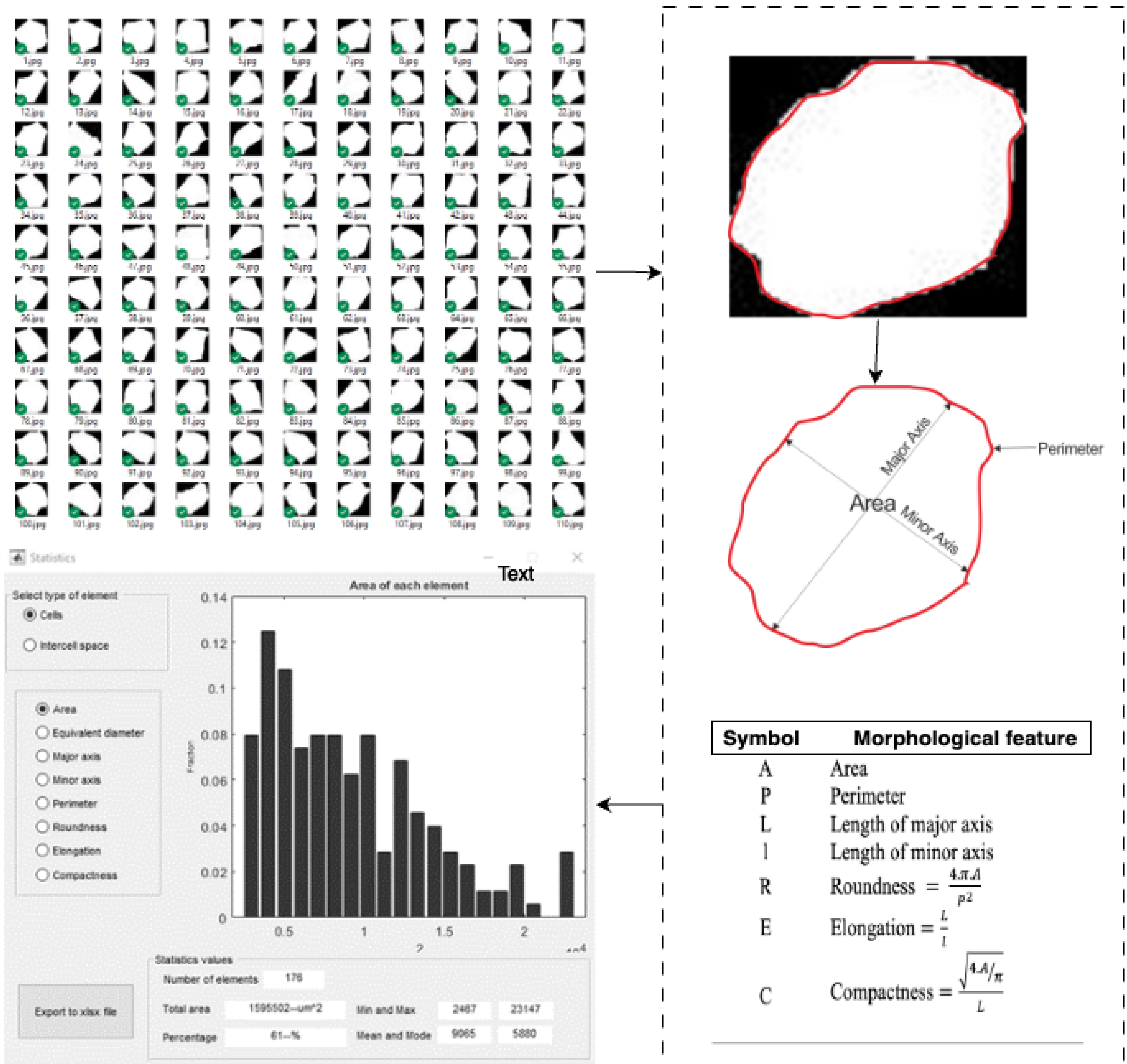

Figure 2. Morphological parameters in the structure elements.

comparison was performed using Tukey's test with a simultaneous confidence level of 95%. The values obtained for the seven microstructural parameters are in the ranges found in other studies such as Calabaza (Mayor et al., 2011; Oblitas et al., 2021; Oblitas-Cruz et al., 2016).

3.2 Effect on microstructural and physicochemical properties according to potato varieties, temperature, and frying time

The standardized Pareto chart in Figure 6 shows the absolute values of the standardized effects from the largest to the smallest one. Potato variety was found to exert the greatest significant effect on the microstructural parameters of area, perimeter, major axis length, minor axis length, roundness, and compactness ($p < 0.05$). Time is the second variable with the greatest effect, which is significant ($p < 0.05$) for the microstructural parameters of area, perimeter, major axis length, minor axis length, and compactness. Finally, temperature exerts a significant effect ($p < 0.05$) only on the parameters of roundness and elongation.

It is observed that temperature causes changes by increasing the area, major axis length, minor axis length, perimeter, roundness, and compactness characteristics in the cells of the Amarilis variety. This behavior is similar to that generated by the Huevo de Indio variety when affected by temperature. If the effect of time is analyzed in these two varieties, it is observed

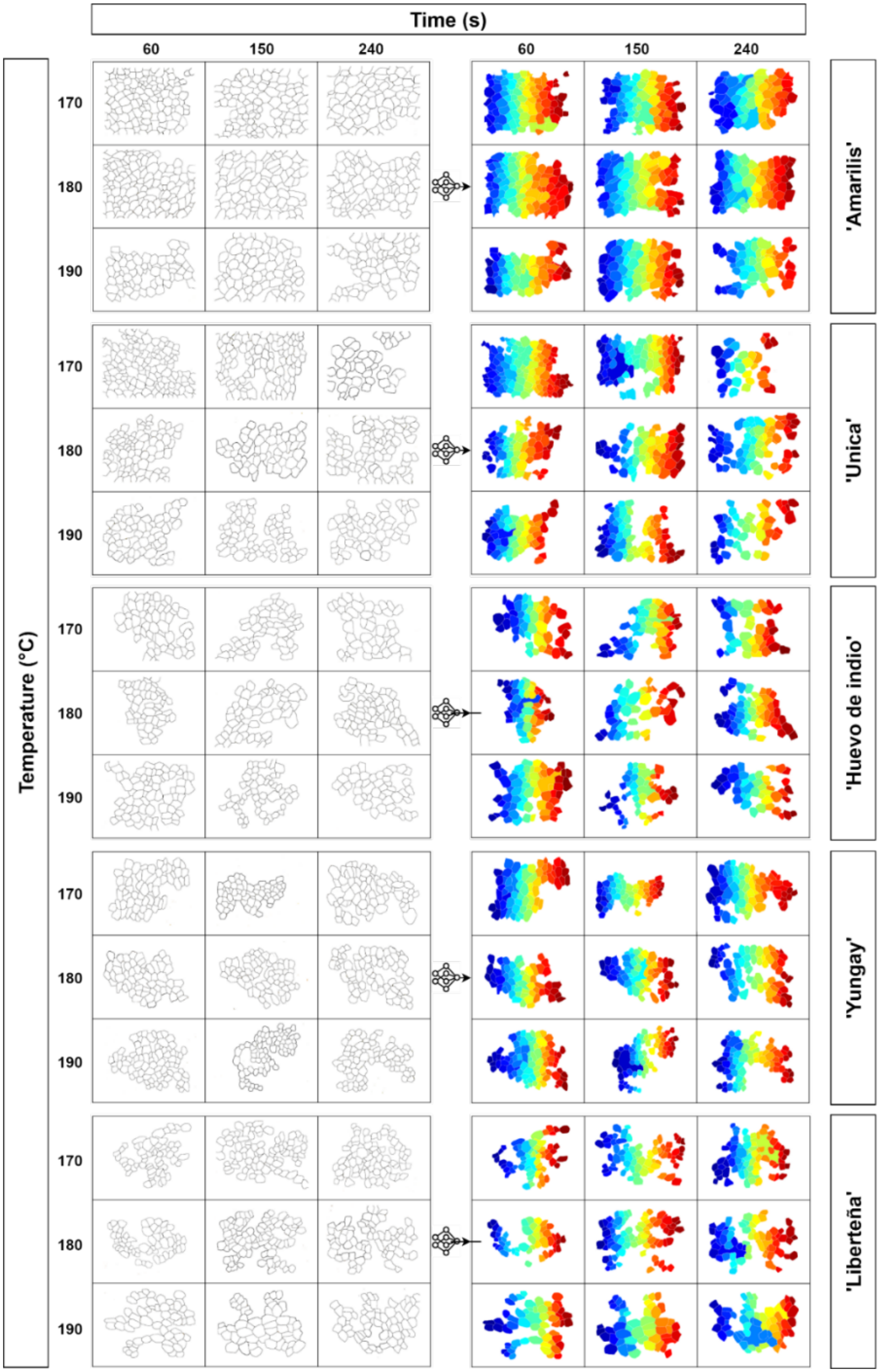

Figure 3. Images of potato cells.

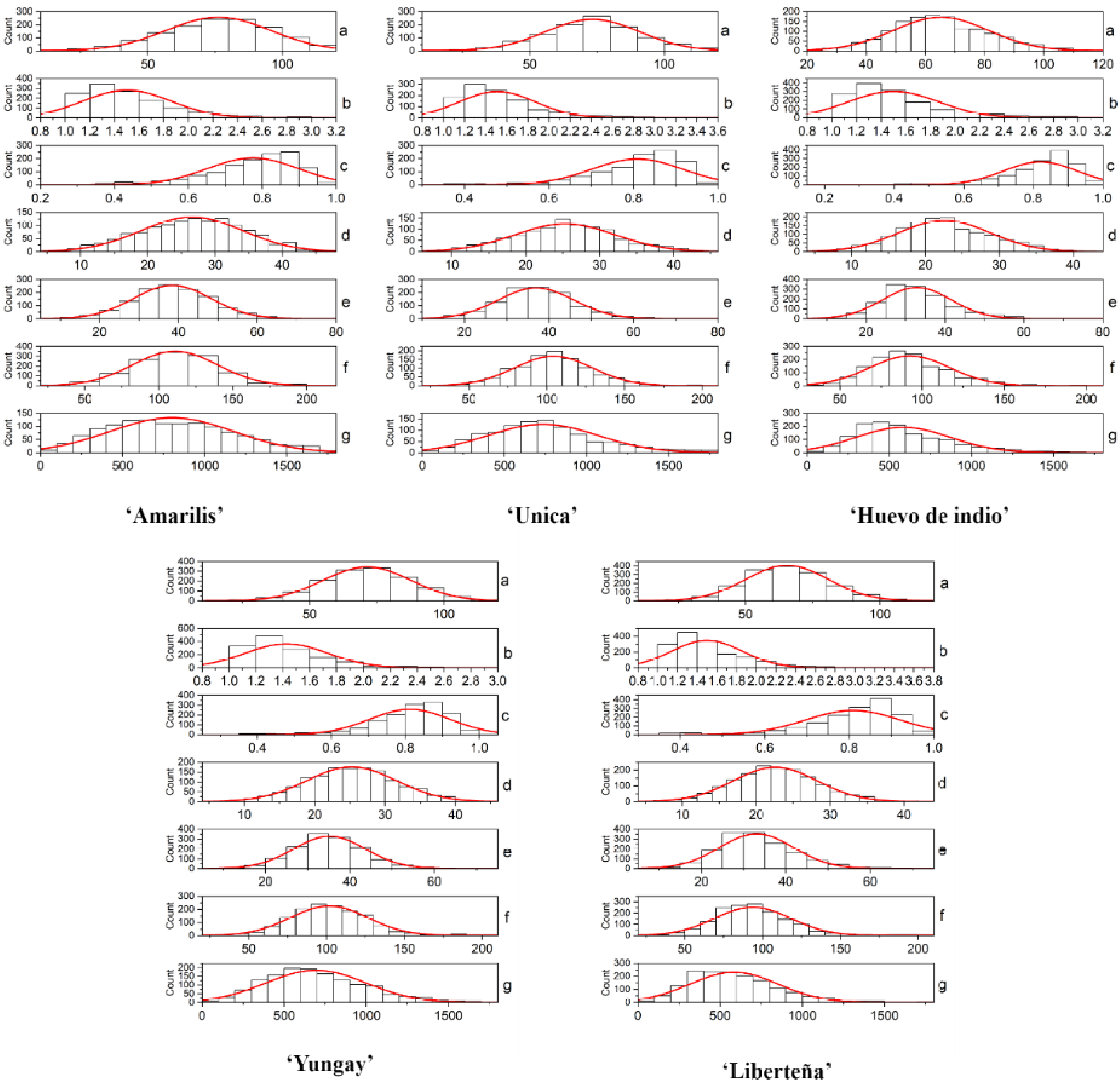

Figure 4. Frequency histograms and average values (normalized) of (A) compactness histograms, (B) elongation histograms, (C) roundness histograms, (D) major axis length averages, (E) minor axis length averages, (F) perimeter averages, and (G) cell area averages.

that the Amarilis variety suffers a positive increase in proportion to time, while the Huevo de Indio variety is not significantly affected by time.

The behavior due to the effect of temperature in the Única, Yungay, and Liberteña varieties is similar because they suffer a reduction in the parameters of area, major axis length, minor axis length, and perimeter in proportion to the increase in temperature. In these three varieties, the parameters of roundness, elongation, and compactness have a small reduction as the temperature increases.

The effect of time is similar for the Única and Yungay varieties, where the increase in this parameter leads to an increase in the area, major axis length, minor axis length, perimeter, roundness, elongation, and compactness characteristics. Likewise, the Huevo de Indio and Liberteña varieties show no change due to the effect of time.

Food microstructure is necessarily related to the technological features of foods. The research by Cruz (Crafts, 1944) already reported that the shrinkage and change levels in fruit cells caused changes in the dimension of the products. The

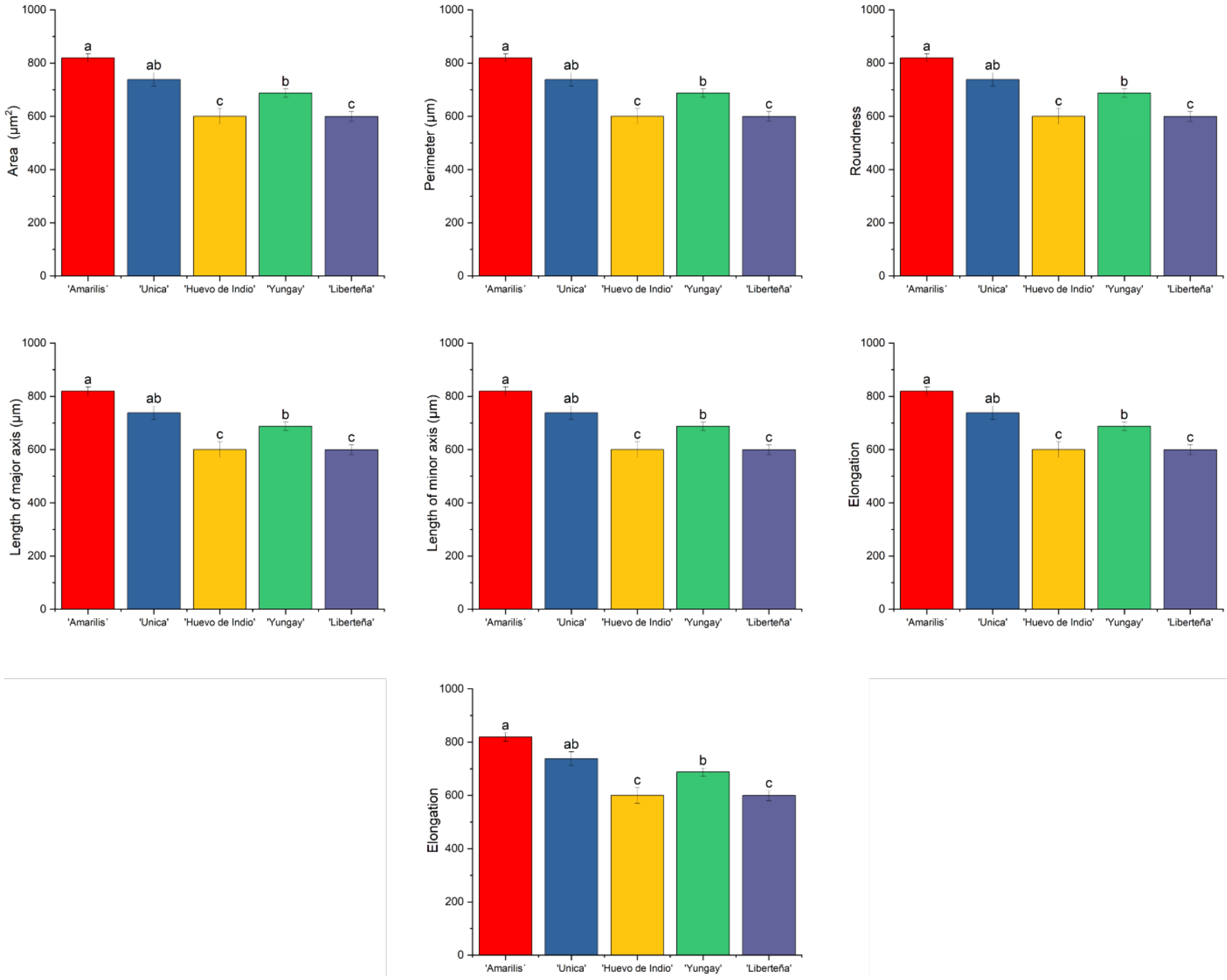

Figure 5. Comparison of microstructural parameters between potato varieties.

progress of this type of study relating microstructure to technological characteristics in food processing was somewhat limited by the few microstructural indicators used in this field which can measure and link these interactions.

The development of microstructural indicators from plant cells using geometrical characteristics of the cells has been part of several studies (Allende et al., 2004; Derossi et al., 2017; Mayor et al., 2011), where it has been shown that the area, equivalent diameter, major axis length, minor axis length, perimeter, roundness, elongation, and compactness obtained from images can represent the microstructural behavior of plant cells. The models presented in these research studies are geometric models that represent the structure of the biological material. However, it was observed that they have deficiencies in finding statistical correlations with the food they represent because the characteristics used, such as the area, have identical values.

3.3 Structure-property-processing relationship

The complex relationships between a wide range of variables must be evaluated individually, especially when trying to predict the frying process behavior. Therefore, from the analyses carried out in this research, both of the microstructural and physicochemical characteristics of the potatoes, correlations were made based on Pearson's correlation values, as seen in Figure 7.

The heat map shown is color-coded with blue and red at different intensities. Blue indicates a negative correlation, red denotes a positive correlation, and increasing intensities indicate an increase in the correlation factor. The linear correlation coefficients (R) are considered weak ($R = 0.0 \sim 0.19$), moderate ($R = 0.2 \sim 0.6$), and strong ($R = 0.6 \sim 1.0$) (Liu et al., 2022). Several studies have used Pearson's correlation to relate microstructural properties with physicochemical parameters such as the relationship between starch gelatinization and texture (Zhao et al., 2022) or in hydrobiological products (Wang et al., 2022).

It is observed that the correlations between the physicochemical variables evaluated generate medium to strong correlations, as do the correlations between the microstructural variables. However, when evaluating the correlations between physicochemical and microstructural variables, it is found that most of them are in the low and medium values,

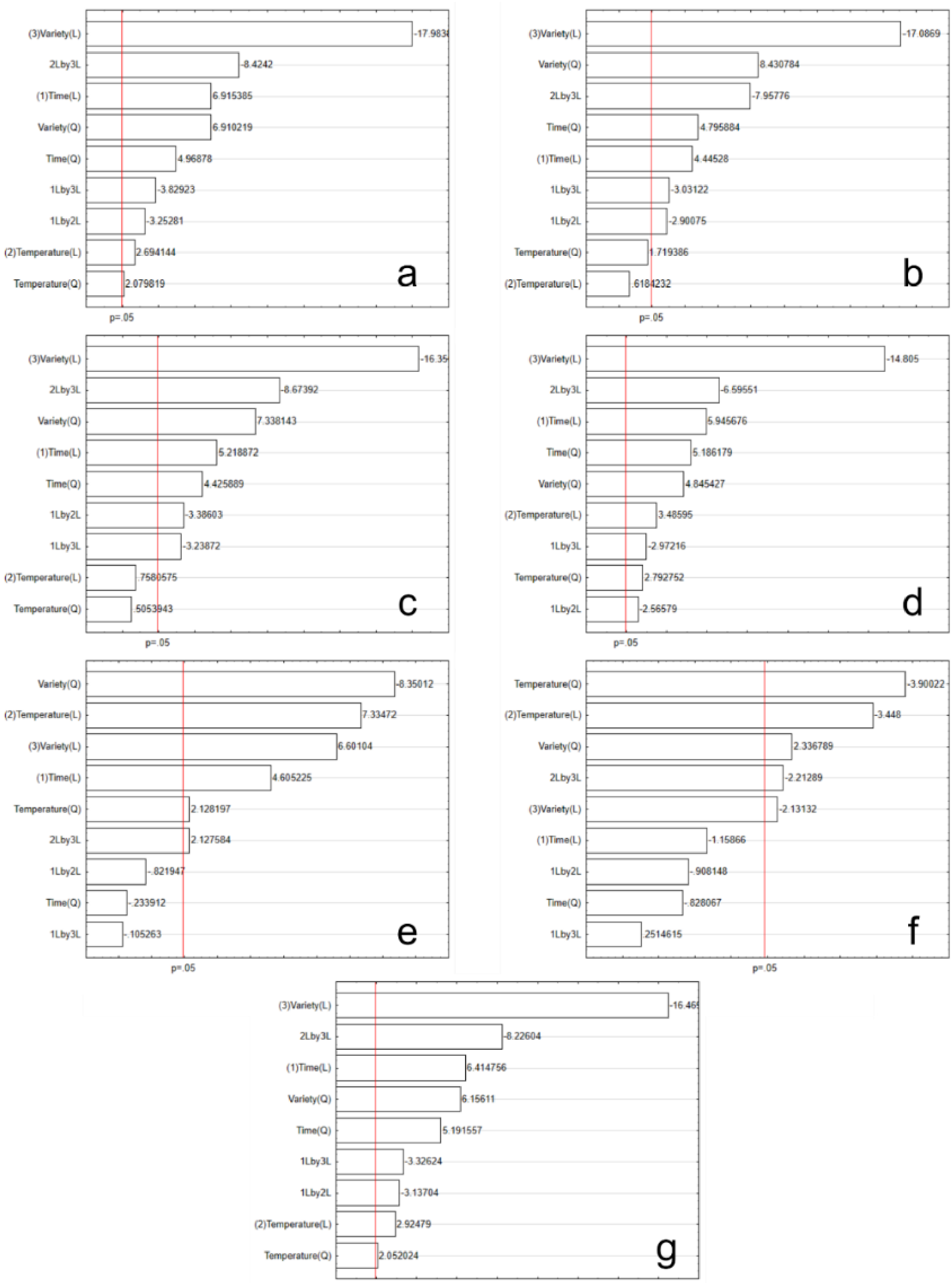

Figure 6. Pareto chart of standardized effect. (A) Area (R^2 = 0.731). (B) Perimeter (R^2 = 0.739). (C) Major axis length (R^2 = 0.734). (D) Minor axis length (R^2 = 0.718). (E) Roundness (R^2 = 0.713). (F) Elongation (R^2 = 0.771). (G) Compactness (R^2 = 0.813)

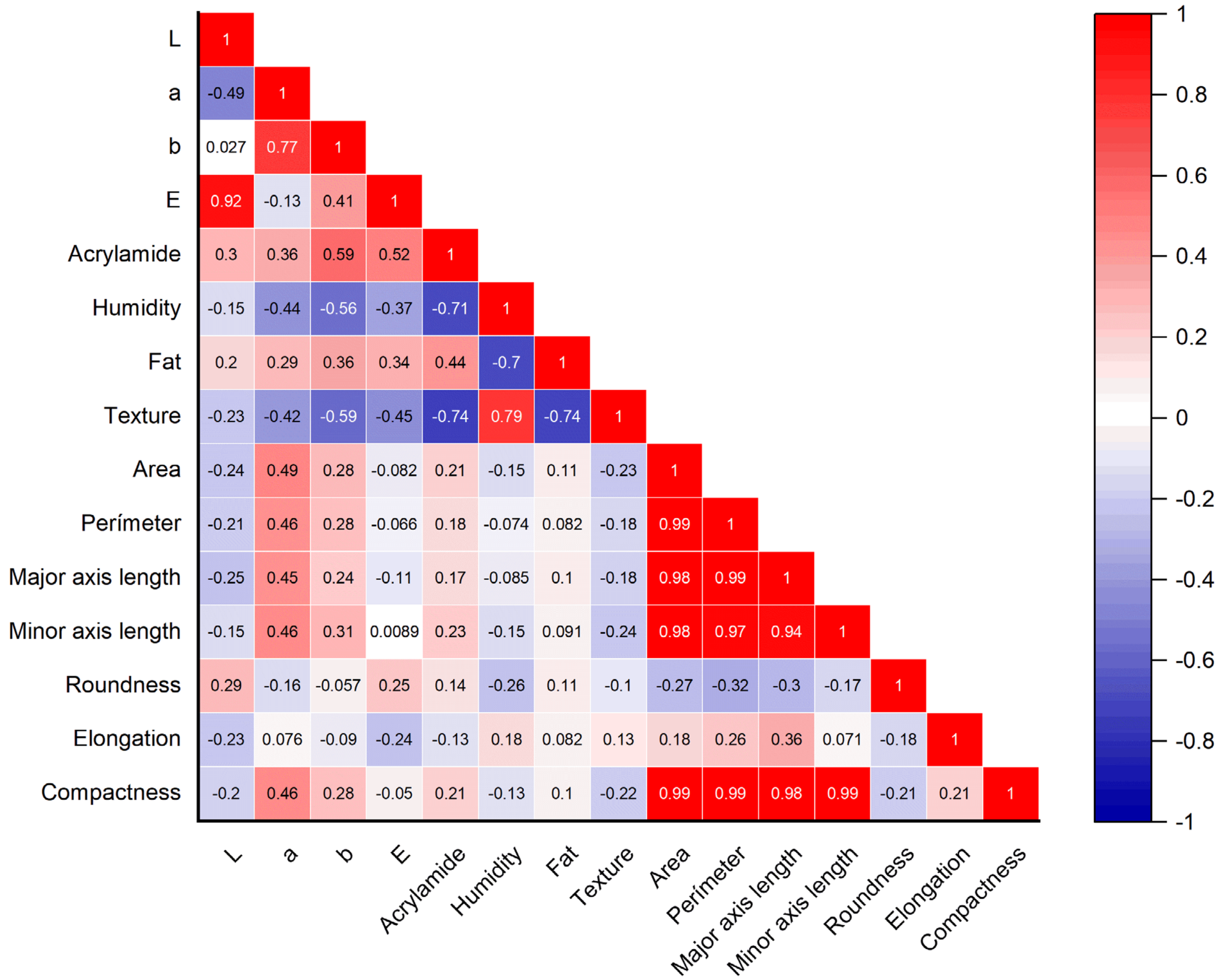

Figure 7. Pearson's factors for the correlation of microstructural versus physicochemical parameters.

with the elongation variable being the least correlated with physicochemical variables, and the variables of major axis length, minor axis length, perimeter, and cell areas are the ones that have a higher linear correlation with the physicochemical variables.

4 CONCLUSION

The results of this study on the effect of the microstructure of potato varieties on physicochemical characteristics give a different start to the use of the geometric model to analyze plant cells as the software designed for the research builds it from a set of approximate polygonal geometries in the limit of shapes taking new variables related to areas and their ratio of aspect and orientation, which together with an artificial intelligence system can discriminate much better the micrographs used. Therefore, the results obtained can be more representative of the potato microstructure and its effect on the frying process.

This initial step is important as it can more accurately represent the tissues, but it is necessary to clarify that this approach is based on a homogeneous tissue. In this study, the same sample areas from the five potato varieties were carefully taken to ensure the homogeneity of the values.

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