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Use of Statistical Quality Control in Experimental Procedures for Mechanical Properties Determination of Vegetative Tissues[1]

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ABSTRACT - Vegetative tissues are viscoelastic materials and suffer from internal and external interferences to obtain data for the characterization of their mechanical properties. Quality control tools are likely to detect internal and external problems in processes and indicate anomalies in the system or sampling points analyzed. This research aims to analyze the use of quality control tools to detect problems in experimental procedures and in sampling data to determine mechanical properties of plant tissues. Uniaxial compression tests were performed to determine the modulus of elasticity and tensile strength under three compression ratios of 0.2 mm/s, 0.4 mm/s, and 0.6 mm/s. Shewart individual and moving range charts were used to analyze internal and external problems, respectively, obtained in the MINITAB software. The results showed that the quality control charts were able to detect sample points that negatively impacted the characterization data.

Key words: Quality Control. Compression Test. Modulus of Elasticity. Maximum Stress Failure. Mechanical Properties.

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INTRODUCTION

Textural quality of agricultural products, such as fruits and vegetables, as well as their degree of ripeness are closely linked to their mechanical properties and can be analyzed as a function of the variation of their modulus of elasticity over time. (Ogawa; Matsuura; Yamamoto, 2015; Shaobao *et al*., 2019; Zhuang *et al*., 2019). Vegetative tissues are entities formed by a biological system that directly impact their mechanical characteristics, exhibiting a viscoelastic behavior far from the optimal conditions of linearity and material geometry and that experimentally is influenced by factors both external and internal to the sample (Fabbro *et al*., 2020; Gazzola *et al*., 2021).

Mechanical attributes of plant tissues are important to determine but challenging to obtain (Nicolai *et al*., 2014). Zdunek and Kurenda (2013) report that the determination of the modulus of elasticity in fruits showed great variation, reaching above 100% of the mean value. Cárdenas-Pérez *et al*. (2016) found a variation of 65% in isolated cells of apple. Ferrari *et al*. (2011) measured the modulus of breakdown stress in fresh melon and their values varied by 7.3%. Li *et al*. (2012) measured the breakdown stress in tomato pulp and found variations of about 23%. Therefore, the possibility of determining the samples that present problems in the sampling data is of great importance and can reduce the oscillation of the characterization data.

Statistical quality control (SQC) is a tool for detecting variations or oscillations in processes, externalizing data that may present special causes and that result in unpredictable behavior and discrepant results, allowing its improvement (Cassia *et al*., 2014; Silva; Voltarelli, 2015; Soela, 2019). The method employs control charts to separate, via graphs, the "random variations," characterized as inherent to the process, from the "special causes". As a process analysis tool, SQC can reduce the oscillation of the variables, aids in the stability of repetitive procedures, and enable searching for process improvements (Maciel; Branco; Werner, 2014). This characterization is conducted by analyzing a number of points that are within acceptable limits, establishing the upper and lower parameters to detect anomalies in the process (Voltarelli; Silva; Zerbato, 2015). Voltarelli (2013) highlights two types of control charts applied to the SQC, being the "individual value", which detects process instabilities (external factors), and the "moving range", which is a complement to the first and determines instabilities in the process resulting from internal factors.

Several authors employed SQC tools to analyze agricultural processes. Arcoverde *et al*. (2017) used control charts to detect anomalous variations in maize sowing, in which they found operational and environmental problems. Voltarelli *et al*. (2018) determined several critical points in the sugarcane billet harvesting process via control charts. Gazzola, Francetto, and Voltarelli (2022) analyzed the Exponentially Weighted Moving Average (EWMA) methodologies and Individual Value control charts to detect anomalies in tractor noises applied to ergonomics of agricultural machinery and the authors reported that both techniques were sensitive in detecting special causes in the process.

This work aims to analyze the use of statistical quality control tools for detecting special variations in experimental procedure for determining the mechanical properties of biological materials. Thus, this study is justified by the application of SQC tools in laboratory procedures, as well as the experimental improvement suggested to the process of mechanical characterization of agricultural products.

MATERIAL AND METHODS

The experimental tests were conducted at the Laboratory of Mechanical Properties of Biological Materials of the School of Agricultural Engineering at the Universidade Estadual de Campinas. Potatoes (*Solanum tuberosum*) were selected as the study material due to their ease of sampling for compression, better continuity, and material homogeneity compared to other types of plant tissues. Specimens were uniformly cut, measuring 12.24 mm in diameter and 19.11 mm in height, using a cylindrical cutter and an end slicer. Tests were conducted in a laboratory with closed windows and doors, and temperature controlled by air conditioning. The compression tests were performed using an EMIC DL-200 MF texturometer with a 2 kN force capacity, coupled to a datalogger to capture data from its sensors. Figure 1 shows the equipment used in the experimental tests. A total of 126 specimens were included in this study, divided into three groups of 42 units each, corresponding to three compression speed rates: V1 = 0.2 mm/s; V2 = 0.4 mm/s, and V3 = 0.6 mm/s. The modulus of elasticity and the maximum tensile strength for each specimen were extracted from the compression tests for further analysis.

To analyze the quality of the mechanical properties data obtained from the sample, this study followed the recommendations of Voltarelli (2013). Thus, the Individual Value control chart was employed to detect anomalies related to external problems (such as problems in conducting the experimental test), whereas the Moving Range chart was employed to detect internal anomalies (such as variations in material constitution). In this study, the mechanical properties of vegetative tissue were analyzed based on maximum tensile strength and modulus of elasticity.

Figure 1 - Equipment employed in the experimental tests. a) Tubes used to extract the specimens; b) Cylindrical base and slicer; c) Instron EMIC DL-200 MF

Source: Prepared by the author (2024)

Individual Value (IV) Control Charts

The individual value (IV) control chart was employed to analyze its potential for detecting external influences in the mechanical characterization process of potatoes. This chart is based on the analysis of the probability of process instability as a function of the mean values of the analyzed lot associated with its standard deviation, which determines the control limits. The upper and lower control limits are estimated using the methodology of the individual value control chart, as defined by Equations (1) and (2), respectively.

$$LSC_{IV} = \mu + L \cdot \sigma \tag{1}$$

$$LIC_{IV} = \mu - L \cdot \sigma \tag{2}$$

In which:

LSC_{IV} = upper control limit for individual value control chart [MPa];

LIC_{IV} = lower control limit for individual value control chart [MPa];

μ = Mean of individual values [MPa];

L = Width of the control limits [MPa];

σ = Standard deviation [MPa];

According to Montgomery (2009), who conducted a study on stability of agricultural processes, control limit width (L) equal to three should be used. The product between the standard deviation and control limit width (L.σ) will be termed as the Total Amplitude (A).

Moving Range (MR) Chart

The moving range (MR) chart is based on analyzing sequential sampling points, enabling the detection of instability caused by intrinsic internal factors. Equation 3 is used to estimate the moving average of amplitudes and, subsequently, Equations 3 and 4 are applied to determine the upper and lower control limits.

$$AM = \frac{|x_i - x_{i-1}|}{N} \tag{3}$$

$$LSC_{MR} = D_3 \cdot AM \tag{4}$$

$$LIC_{MR} = D_4 \cdot AM \tag{5}$$

In which:

AM = Average sample moving range [MPa];

LSC_{MR} = upper control limit for moving range control chart [MPa];

LIC_{MR} = lower control limit for moving range control chart [MPa];

Voltarelli (2013), in studies related to moving range control chart applied to agricultural proccess, suggested employing the value of 3.267 to D_3 (upper limit) and 0 to D_4 (lower limit).

Statistical analysis

The statistical analysis of individual values included mean population sample (μ), standard deviation (σ), total amplitude (A), coefficient of variation (CV), and the Ryan-Joiner normality test (RJ). The RJ was employed to estimate the proximity between individual points and the data probability estimate line, providing greater rigidity for analysis when the coefficient correlation is closer to 1.0 (Tavares *et al*., 2015). Meanwhile, the statistical analysis for moving range charts included the average general moving range amplitude (AM) and total amplitude range, which is numerically represented by the upper control limit for the moving range control chart (LSC_{MR}). Statistical data and control chart graphics were obtained with the MINITAB software.

RESULTS AND DISCUSSION

Table 1 shows the statistical values for the maximum failure stress and elasticity modulus of potatoes obtained from the laboratory test data.

The characteristic value of the maximum tensile strength and modulus of elasticity for the potato is represented by the mean of the sample values individual. For these properties, the compression ratio of 0.4 mm/s (1,364 MPa and 5,276 MPa) obtained higher averages than the compression ratio of 0.2 mm/s (1,169 MPa and 4,543 MPa) and the compression ratio of 0.6 mm/s (1,050 MPa and 4,338 MPa). The last two speeds mentioned presented values very close to each other and the speed of 0.4 mm/s differed from the others. This behavior was also observed for the averages of the general moving range amplitude (AM). The standard deviation data followed the same trend, with the data for the velocity of 0.4 mm/s showing greater dispersion compared to the velocities of 0.2 mm/s and 0.6 mm/s. The statistical data showed a behavior that agreed with what was illustrated by the control charts. However, the advantage of using control charts is their capacity to identify points with potential problems.

Regarding amplitude of the control bands for both charts (A and LSC_{MR}), it is noteworthy that the compression ratio of 0.4 mm/s presented the widest range. However, it also showed a greater number of points outside the control limits, demonstrating that it was a more unstable test process. In contrast, the compression ratio of 0.6 mm/s presented the narrowest range and showed fewer points outside the established control limits, i.e., it is suggested that this compression ratio was less impacted by external and internal factors, resulting in greater data stability.

The coefficient of variation results for the compression ratio of 0.6 mm/s showed variation indices of 9% for tensile strength and 7.6% for modulus of elasticity. The compression ratio of 0.2 mm/s showed a variation of 13% for the mechanical properties analyzed, whereas the compression ratio of 0.4 mm/s of 19.%. When comparing these coefficients of variation with those found by other authors, the results can be considered positive for determining the modulus of elasticity, as those studies found variation indices ranging from 65% to 95% (Cárdenas-Pérez *et al*., 2016). Similarly, tensile strength results were within the expected range, with authors indicating variations ranging from 7.3% to 23% (Ferrari *et al*., 2012; Li *et al*., 2011).

Finally, the Ryan-Joiner (RJ) normality test results were close to 1 (one), indicating that the sample data values tend to be normal for all cases. Thus, it is possible to state, according to the RJ, that individual control charts can be adopted as a quality control tool for experimental procedures aimed at determining mechanical properties of vegetative tissues.

Figures 2, 3, and 4 show the individual value (IV) and moving range (MR) charts for the determination of the maximum tensile strength under compression velocities of 0.2 mm/s, 0.4 mm/s, and 0.6 mm/s, respectively.

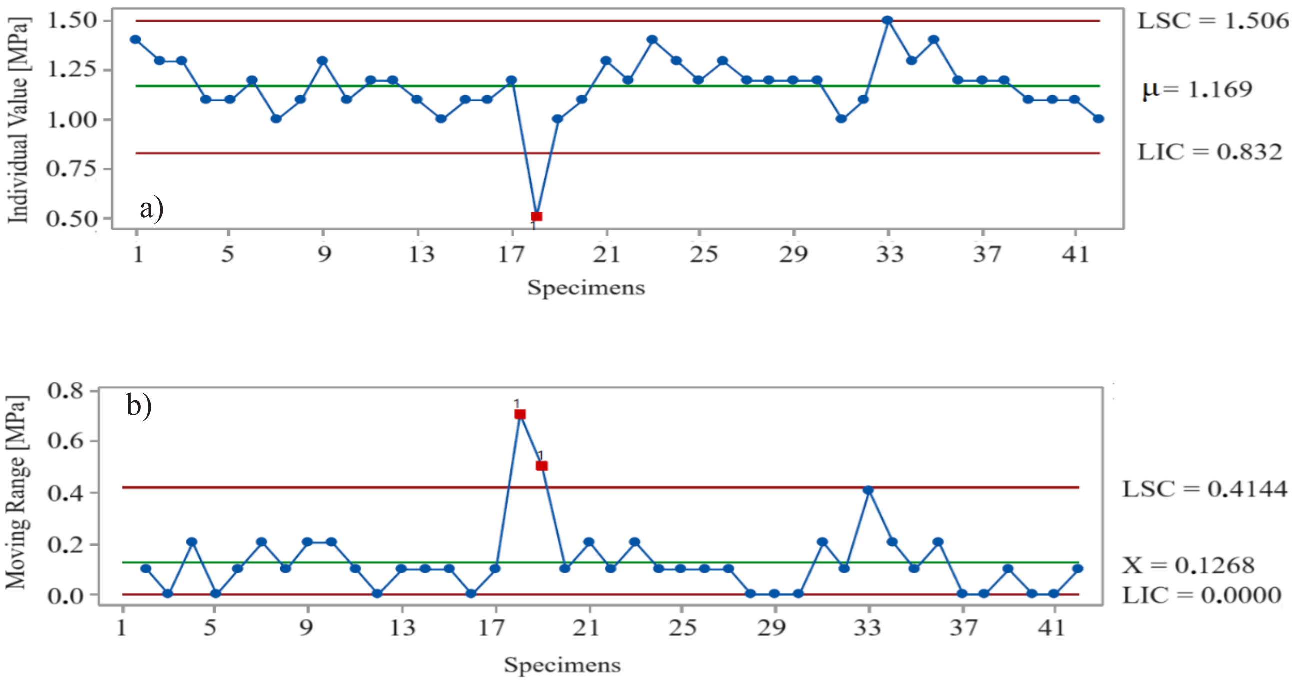
Comparing graphs behavior shown in Figures 2, 3, and 4, it is noted that in the Individual Value (IV) control charts, all compression ratios analyzed indicated points with maximum tensile strength data outside the established limits. For the compression ratios of 0.2 mm/s and 0.6 mm/s, single points below the established limit were found (Specimens 18 and 36, respectively). In contrast, for the compression ratio of 0.4 mm/s, two points below and above the control limits were noted (Specimens 2 and 20, respectively). In the Moving Range (MR) chart, a higher frequency of points outside the control limit was observed, with the compression ratio of 0.2 mm/s presenting two points above the limit, whereas the compression ratio of 0.4 mm/s showed three points. However, the compression ratio of 0.6 mm/s showed no points outside the control limits.

Table 1 - Statistical data obtained by the quality control charts

Parameter	V1 = 0.2 mm/s		V2 = 0.4 mm/s		V3 = 0.6 mm/s	
	σu [MPa]	E [MPa]	σu [MPa]	E [MPa]	σu [MPa]	E [MPa]
μ [MPa]	1.17	4.54	1.36	5.28	1.05	4.34
A [MPa]	0.67	2.49	1.04	4.29	0.48	1.92
σ [MPa]	0.16	0.59	0.27	1.04	0.10	0.33
CV [%]	13.68	13.00	19.68	19.78	9.22	7.63
RJ	0.939	0.923	0.985	0.992	0.997	0.997
LSCMR [MPa]	0.41	1.53	0.64	2.64	0.29	1.18
AM [MPa]	0.13	0.47	0.20	0.81	0.09	0.36

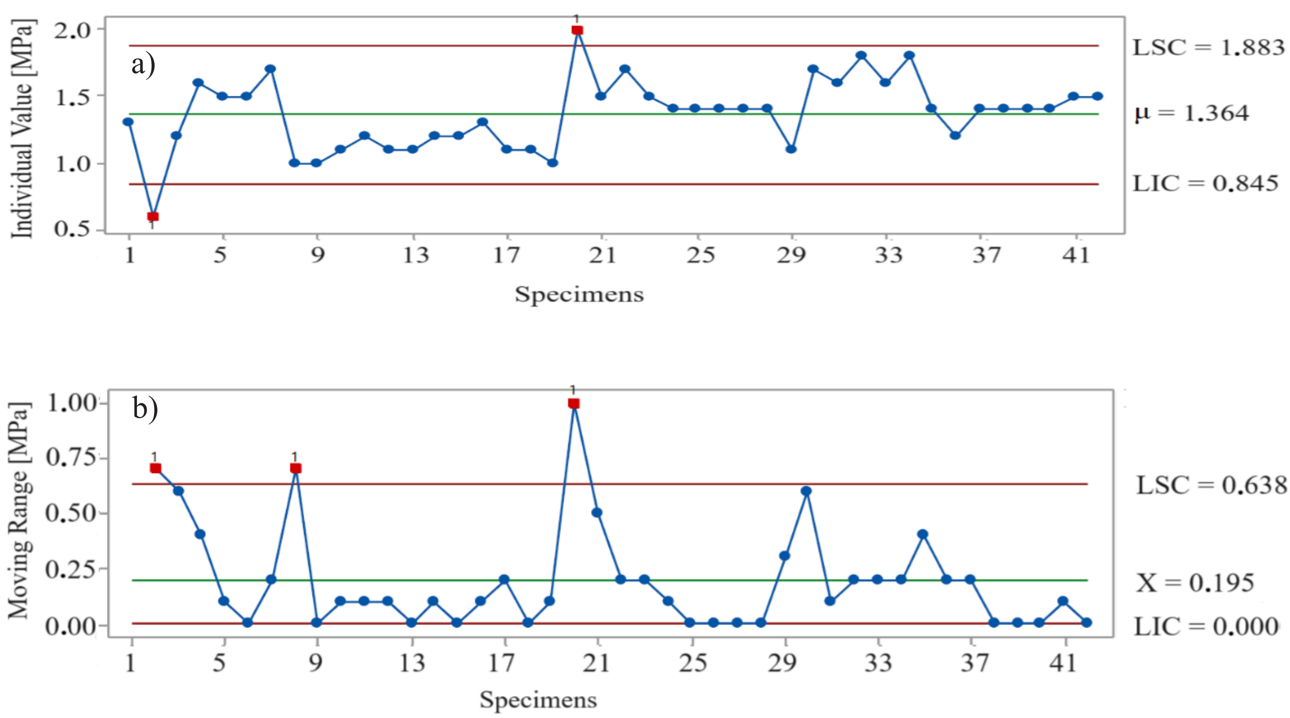
Source: Prepared by the author (2024). μ – Mean population sample for IV; A - Total amplitude of the control range for IV; σ – Standard Deviation; R.J. – Ryan-Joiner normality test; LSC_{MR} – Total amplitude range of MR control chart; AM – Average of the general moving range amplitude

Figure 2 - Statistical Quality Control Charts for determining the maximum tensile strength of potatoes at a compression ratio of 0.2 mm/s: a) Individual Value Control Chart; b) Moving Range Chart



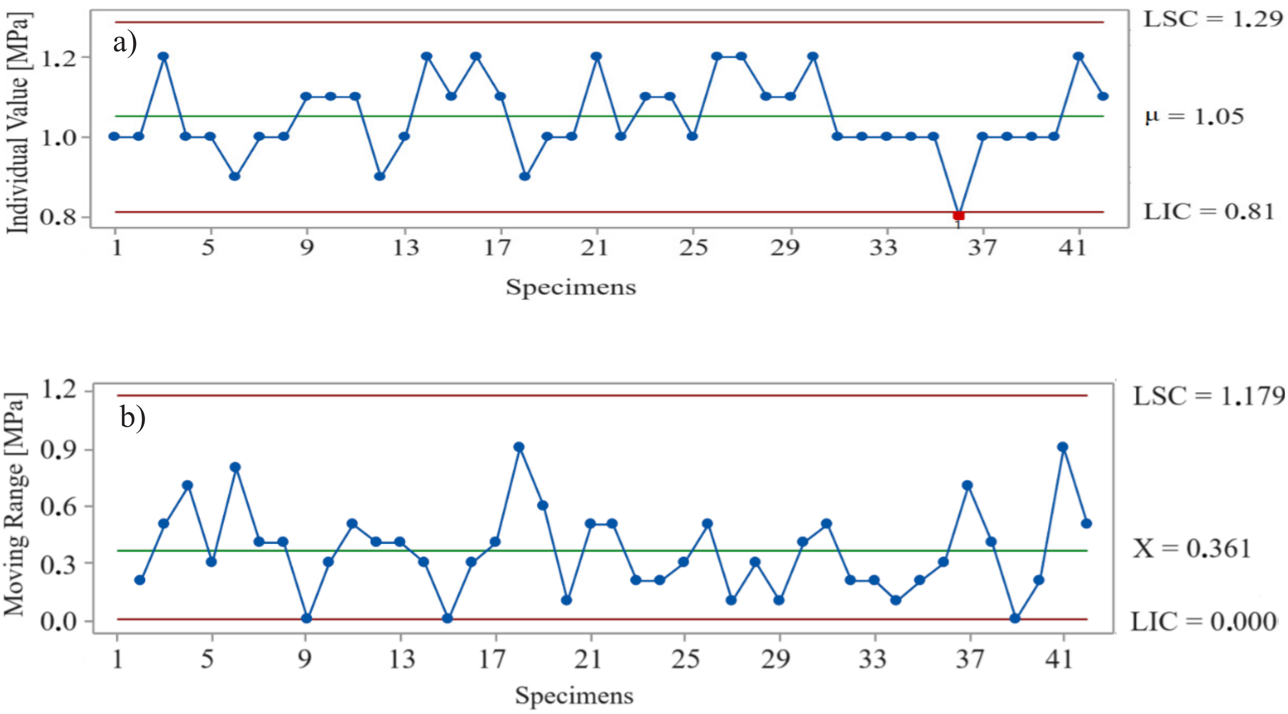
Source: Prepared by the author (2024)

Figure 3 - Statistical Quality Control Charts for determining the maximum tensile strength of potatoes at a compression ratio of 0.4 mm/s: a) Individual Value Control Chart; b) Moving Range Chart



Source: Prepared by the author (2024)

Figure 4 - Statistical Quality Control Charts for determining the maximum tensile strength of potatoes at a compression ratio of 0.6 mm/s: a) Individual Value Control Chart; b) Moving Range Chart



Source: Prepared by the author (2023)

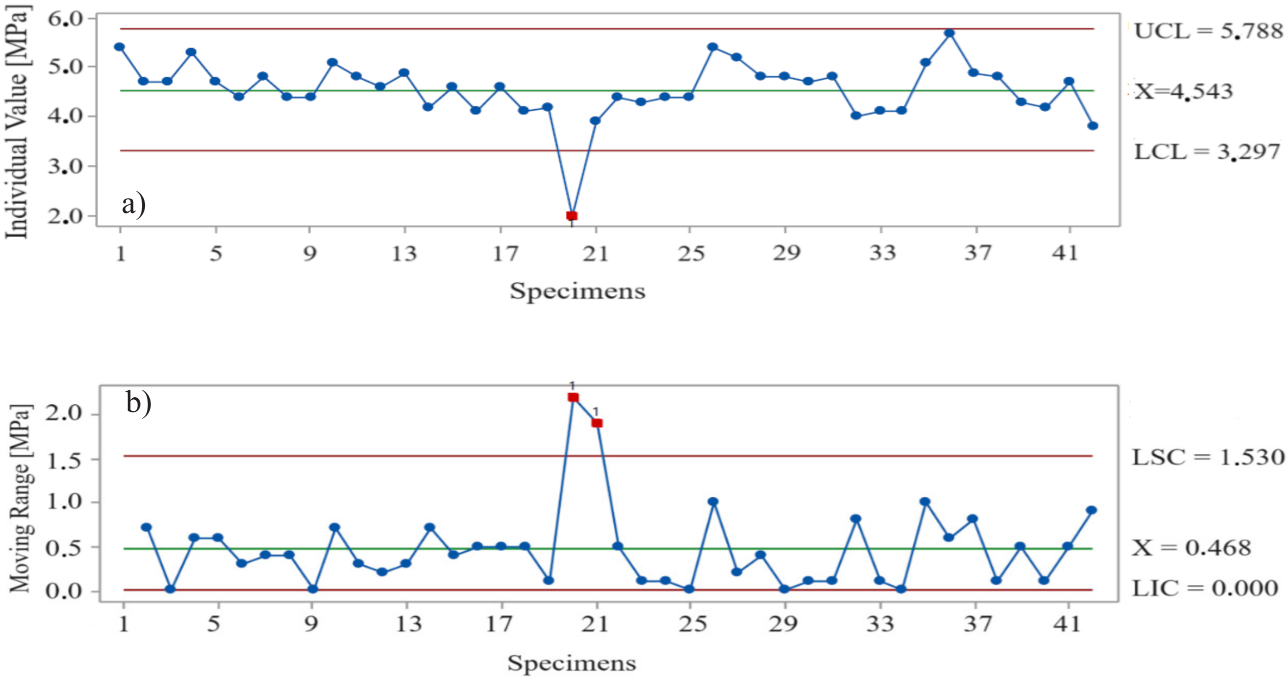
Analyzing the behavior of both quality control charts, it was first noticed that the IV control chart indicated that, for determining maximum tensile strength, internal factors impacted the mechanical characterization of the materials regardless of the compression ratio applied to the specimens. This can be explained by considering that vegetative tissues show some kind of variability in their internal formation, as will be better discussed later. In contrast, the MR chart showed that the compression ratio of 0.4 mm/s had its sample data more impacted by external factors compared to compression ratio of 0.2 mm/s, which was slightly impacted. Meanwhile, the compression ratio of 0.6 mm/s did not present points outside the established control limit. Although the MR graphs indicate that high compression ratios can eliminate the impact of external factors, this cannot be confirmed since the intermediate compression ratio (0.4 mm/s) showed the highest number of sample points outside the control limits, followed by the lowest compression ratio.

The graphs also draw attention to two sampling points that are worth highlighting: points 18 and 20 for the 0.2 mm/s and 0.4 mm/s compression ratios, respectively. Differing from the other sample points analyzed, these two cases presented data outside the established limits on both charts, indicating that both external and internal factors impacted the sample data. In addition, these points were farther from the control limits compared to the other sample data. Therefore, the quality control charts were able to detect the extent to which each point was outside the control limit and how such deviation may impact the results of mechanical characterization of vegetative tissues. Thus, for sampling points that present such behavior, the control charts can show sample points that present mechanical behavior problems and suggest the potential need of discarding that sample.

Figures 5, 6, and 7 show the IV and MR control charts related to potato modulus of elasticity on compression ratios of 0.2 mm/s, 0.4 mm/s, and 0.6 mm/s, respectively.

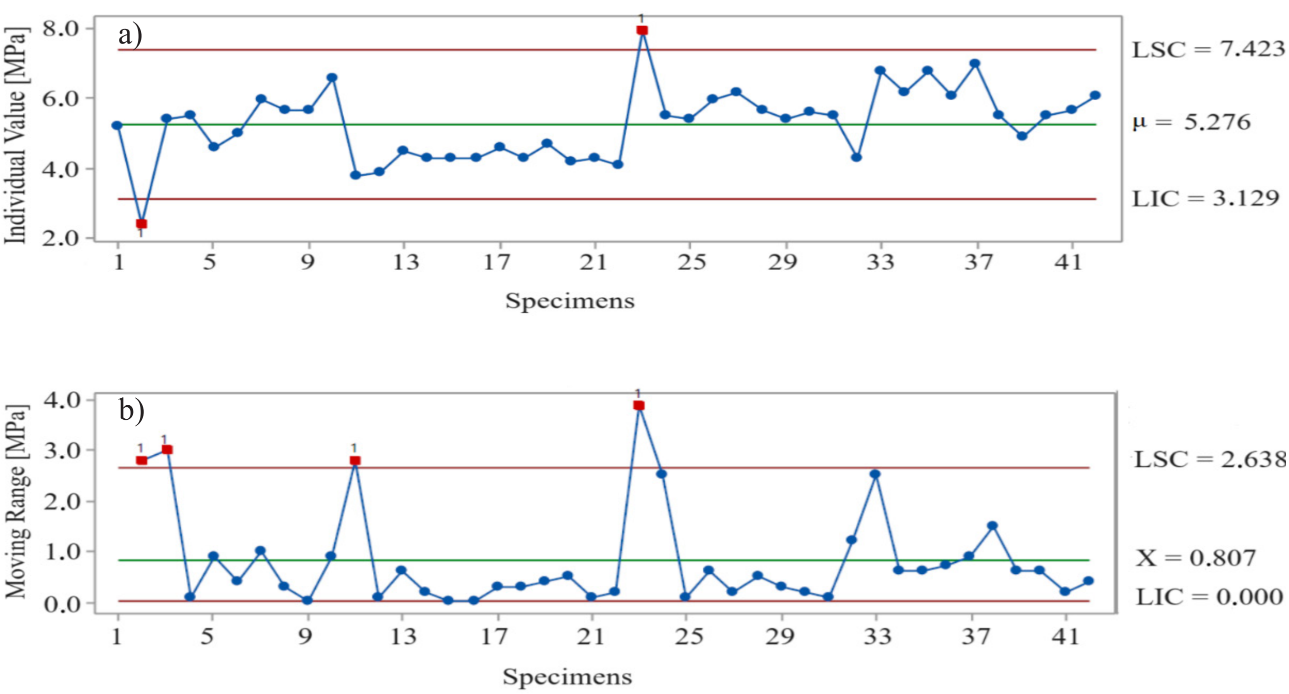
Analyzing the individual control charts presented in Figures 5 to 7 for determining the modulus of elasticity of potatoes, it was found that at a compression ratio of 0.2 mm/s, Sample 20 presented a point below the established limit. At a compression ratio of 0.4 mm/s, Sample 23 showed a modulus of elasticity above the control limit. The compression ratio of 0.6 mm/s showed no data points outside the established limits. Regarding the MR chart, the graphs behavior for modulus of elasticity of the sample data was similar to what occurred in the IV control charts, with points out of control detected only for the compression ratios of 0.2 mm/s and 0.4 mm/s. However, a higher intensity of points were noted outside the control limit, with two points above the control limit for the compression ratios of 0.2 mm/s (Samples 20 and 21) and four points for the compression ratio of 0.4 mm/s (Samples 2, 3, 11, and 23).

Figure 5 - Statistical Quality Control Charts for determining modulus of elasticity of potatoes at a compression ratio of 0.2 mm/s: a) Individual Value Control Chart; b) Moving Range Chart



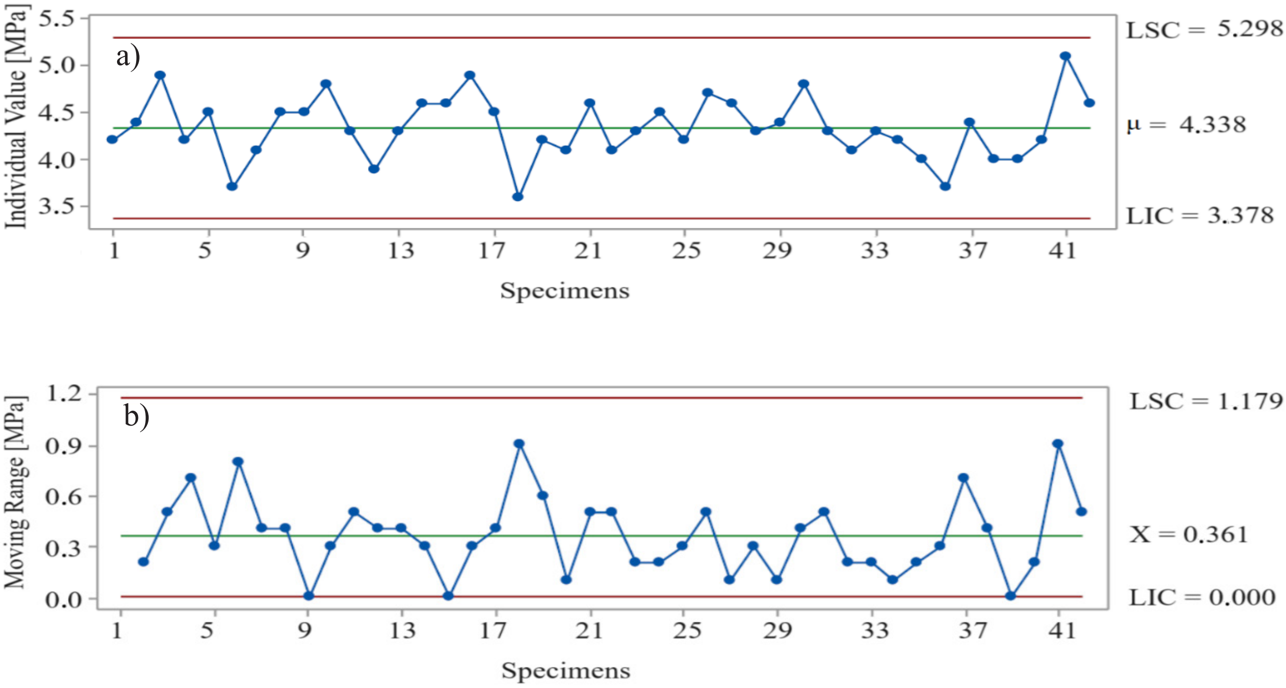
Source: Prepared by the author (2024)

Figure 6 - Statistical Quality Control Charts for determining modulus of elasticity of potatoes at a compression ratio of 0.4 mm/s: a) Individual Value Control Chart; b) Moving Range Chart



Source: Prepared by the author (2024)

Figure 7 - Statistical Quality Control Charts for determining modulus of elasticity of potatoes at a compression ratio of 0.6 mm/s: a) Individual Value Control Chart; b) Moving Range Chart



Source: Prepared by the author (2024)

Comparing the behavior of the IV and MR control charts for determining the modulus of elasticity, it was observed that higher compression ratios result in a more stable process for obtaining data to characterize the mechanical properties of vegetative tissues, reducing the impact of external and internal factors during the laboratory testing process. However, as mentioned above, this statement cannot be definitive, as the intermediate compression ratio presented a greater number of sample points outside the control limits. It is also worth mentioning that, as noted above, the quality control charts presented points that deserve to be highlighted in the analysis. Sampling point 20 for a compression ratio of 0.2 mm/s and sampling point 23 for a compression ratio of 0.4 mm/s were both outside the established control limits for both charts, as well as their deviation from the mean data being greater than the other sampling points obtained. This is in line with what was observed for the control charts of rupture stresses, indicating a situation in which internal and external factors jointly impact certain sample data.

In general, based on the behavior of the graphs presented by the quality control charts analyzed, it can be stated that the individual and MR control charts were able to detect impacts from external and internal factors in determining the mechanical properties of vegetative tissues. This is evidenced by the fact that specimens showed varied behaviors, with some data points outside the established control limits, as well as situations in which no internal nor external impacts were found, as it was observed at a 0.6 mm/s compression ratio. The intermediate compression ratio of 0.4 mm/s presented a greater instability in the results obtained compared to the low compression ratio of 0.2 mm/s, as evidenced by the higher number of points outside the established control limits. On the other hand, the compression ratio of 0.6 mm/s showed the greatest stability, showing the lowest number of points outside the established control limits. This behavior suggests that the explored control charts are sensitive to detecting anomalies in the sampling data, identifying and correcting data that can impact the determination of characteristic mechanical properties.

Analyzing the internal and external factors that may interfere with the tests, some authors have reported problems that impact the determination of the mechanical properties of vegetative tissues. Among the special causes cited, moisture content of the analyzed material and internal failures of the specimen are highlighted. Zhu and Melrose (2003a) have stated that mechanical properties of biological tissues are impacted by the turgor pressure of plant cells. Similarly, internal failure problems in potatoes were observed by Diehl, Hamann, and Whitfield (1980), who suggested that volumetric deformations impact shear stress in plant tissues. These findings corroborate those observed by Babarisa and Ige (2012), who claim that moisture content impacts the shear stress of fruits and vegetables.

When analyzing external factors, we highlight the compression ratio. The behavior of the sample data in the quality control charts suggests that, at higher compression ratios, external factors may have less impact on laboratory test results. Zhu and Melrose (2003b) explain that lower compression ratios allow the fluidic part of plant tissues to have a relative mobility. On the other hand, higher compression ratios can get trap fluid in the cells, causing the tissue to behave differently. Although temperature was not considered in this research—as the tests were conducted in a controlled environment to avoid such variations—the impact of compression ratios remain inconclusive. This is because the data showed no logical consistent behavior, showing variations in mechanical properties according to the applied compression ratio. According to the results, the highest compression ratio of 0.6 mm/s presented more reliable mechanical property data, followed by the compression ratio of 0.2 mm/s, which showed more concise data, closer to the results obtained at 0.6 mm/s than at 0.4 mm/s. The control charts indicated that the intermediate compression ratio (0.4 mm/s) presented a higher number of points outside the control limits, with conflicting data between the compression ratios of 0.2 mm/s and 0.6 mm/s. In this case, it was expected that the sample data at 0.4 mm/s would present intermediate mechanical property values between those observed at compression ratios of 0.2 mm/s and 0.6 mm/s.

The higher number of data points outside the control limits in the MR chart compared to the IV chart for the compression ratio of 0.4 mm/s suggests that the impact is more likely to be of an internal nature than an external factor. Samples with internal failure problems are hardly detectable via human vision unless they are on the surface of the specimen. However, the behavior of the control charts indicated the occurrence of anomalies in the results obtained for the compression ratio of 0.4 mm/s, which could indicate that some data need to be discarded.

CONCLUSION

According to the analysis above, it can be concluded that the Individual Value and Moving Range quality control charts are appropriate tools for analyzing the quality of sample data in the mechanical characterization of vegetative tissues. These control charts can identify internal and external problems and detect isolated sampling points in which problems occurred, as well as sample lots that may negatively impact the average of the characterizing data, as observed at the compression ratio of 0.4 mm/s in this study. The control charts clearly illustrate recurring problems in the tests and, via graphs, provide the executor with data needed to make decisions regarding the test methodology and make corrections to laboratory procedures. The statistical data indicated that the coefficient of variation was within the expected range, suggesting that the laboratory procedure was well applied. However, the probability tests suggest that more repetitions should be performed. Even so, we consider that the technique should be regarded as a quality control tool for experimental tests aimed at obtaining mechanical properties of biological materials.

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