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Exploring physical quality parameters of 'Gala' apples through path analysis

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ABSTRACT: Apple holds significant agricultural and economic importance, ranking among the most extensively cultivated fruits worldwide. In Portugal, it plays a vital role, with the Alcobaça apple, recognized with a Protected Geographical Indication (PGI), standing out for its exceptional quality and deep-rooted tradition. Apple production in the country bolsters exports, drives rural employment, and fosters technological innovation in the agricultural sector. Path analysis has been widely used to understand production better and determine the relationships between fruit attributes and their constituents. It stands as a valuable tool for improving postharvest handling practices. This study aimed to investigate the relationships among the physical quality parameters of 'Gala' apples from Alcobaça (Portugal), which can be helpful in the classification of these fruits. The path analysis was conducted on fruits produced in two commercial orchards in 2018, 2019, and 2020. The physical parameters evaluated were fruit mass (g), height (mm), diameter (mm), height/diameter ratio, volume (cm^3) and firmness. The Pearson correlation network was used to estimate the association between the physical variables and to express the results graphically. The correlation network was used to correct for multicollinearity among the variables. The results of the Pearson correlation indicated a strong positive relationship between the fruit mass and the other variables. Path analysis revealed that the mass of the apples strongly influences the diameter, height, and volume. Thus, the mass variable, identified through direct and indirect selection of primary components through path analysis, proves valuable for postharvest selection and classification of 'Gala' apples.
Keywords: *Malus domestica*; postharvest selection; statistical tool.

Análise dos parâmetros de qualidade física das maçãs 'Gala' através da análise de trilha

RESUMO: A maçã tem uma importância agrícola e econômica significativa, sendo um dos frutos mais cultivados em todo o mundo. Em Portugal, desempenha um papel vital, com a Maçã de Alcobaça, reconhecida com a Indicação Geográfica Protegida (IGP), destacando-se por sua qualidade excepcional e tradição profundamente enraizada. A produção de maçãs no país não apenas fortalece as exportações, mas também impulsiona o emprego rural e promove a inovação tecnológica no setor agrícola. A análise de trilha tem sido amplamente utilizada para compreender melhor a produção e determinar as relações entre os atributos dos frutos e os seus constituintes. Constitui uma ferramenta valiosa para melhorar as práticas de manuseamento pós-colheita. Este estudo teve como objetivo investigar as relações entre os parâmetros de qualidade física de maçãs 'Gala' de Alcobaça (Portugal), que podem ser úteis na classificação destes frutos. A análise de trilha foi realizada em frutos produzidos em dois pomares comerciais diferentes, durante os anos de 2018, 2019 e 2020. Os parâmetros físicos avaliados foram massa do fruto (g), altura (mm), diâmetro (mm), relação altura/diâmetro e volume (cm^3). A rede de correlação de Pearson foi utilizada para estimar a associação entre as variáveis físicas e para expressar os resultados graficamente. A rede de correlação foi utilizada para corrigir a multicolinearidade entre as variáveis. Os resultados da correlação de Pearson indicaram uma forte relação positiva entre a massa do fruto e as outras variáveis. A análise de trilha revelou que a massa das maçãs influencia fortemente o diâmetro, a altura e o volume. Assim, a variável massa, identificada através da seleção direta e indireta de componentes primários através da análise de trilha, revela-se valiosa para a seleção e classificação pós-colheita de maçãs 'Gala'.
Palavras-chave: *Malus domestica*; ferramenta estatística; seleção pós-colheita.

1. INTRODUCTION

Apple (*Malus domestica* Borkh.) belongs to the family Rosaceae, a widely cultivated fruit. According to the latest available data, the total world apple production in the 2022/2023 crop year was about 83 million tons (STATISTA, 2024). Apples are the third most important fruit crop worldwide in production, following bananas and watermelons. In Portugal, the apple is a permanent crop that occupies a prominent position in production, followed by

orange and pear. The estimated average production is 265,000 tons per year, 0.4% of world production. In 2021, according to agricultural statistics published by the National Statistics Institute (INE, 2021), 368,200 tons of apples were produced, the second-highest production in the last 35 years.

Currently, there are 4 Protected Geographical Indications (PGI) for apples in the country, of which the 'Maçã de Alcobaça' (Alcobaça apple) represents 25% of the total national production. The PGI includes different varieties of apples, 'Casa Nova', 'Golden Delicious', 'Red Delicious', 'Gala', 'Fuji', 'Granny Smith', 'Jonagold', 'Reineta' and 'Pink', all produced in Alcobaça, located in the western region of mainland Portugal. This region boasts characteristic edaphoclimatic conditions that contribute to important attributes of apples, including elevated consistency and crispness, high sugar content and intense aroma (APMA, 2020).

Among these apples, the 'Gala' cultivar is in high demand in the national and international markets. Apples have a varied and well-balanced composition and can be incorporated into a healthy diet due to their content of water, sugars, organic acids, vitamins, minerals, dietary fiber and antioxidants properties (ASMA et al., 2023; OSZMIAŃSKI et al., 2019; NETO et al., 2020).

The development of the apple tree can be affected by several genetic, environmental, and agronomic factors, which can directly influence the quality of the fruit, including characteristics like coloration, pulp chemical composition, flavor, shape, size, texture, and preservation, among others (CHAPLOUTSKYI et al., 2023; VERMA et al., 2024). Changes in the physical variables of the apples, such as mass, size and diameter, affect the uniformity of the harvested fruits. Indeed, a significant challenge 'Gala' apple producers face is the caliber inconsistency, leading to uneven production and complicating the sorting and selection process in the packing houses.

Thus, studying the physical quality parameters of apples and understanding how they correlate with each other is very important, both for predicting certain changes in one depending on another and for making timely decisions to correct or minimize the consequences arising from these changes. Using technologies that enable high-resolution data collection and analysis, such as algorithms, spatial variability, or path analyses, assists precision agriculture.

This study uses path analysis, a multivariate statistical tool, to investigate the relationships between different physical properties of 'Gala' apples and their mass, indicating criteria for the direct selection of more attractive or uniform fruits. The technique of estimating correlations between variables is widely used to determine how to enhance important attributes for crop quality. However, a third variable or a group of variables can influence the correlation between two variables. Path analysis is the most suitable technique to remove the effect of these other variables. It allows the correlation coefficient between two variables to be broken down into direct and indirect effects. The variable to be used as an indirect selection criterion should have a high correlation with the primary dependent variable, a high immediate effect, and be in the same direction as the correlation, besides being more accessible to measure (NASCIMENTO et al., 2024).

Several authors have used path analysis to evaluate various economically significant fruits, including apples (Verma et al., 2024), grapes (Rodrigues et al., 2024), mango (Lal et al., 2017), strawberries (Singh et al., 2018), lemon (Malikouski et al., 2021), blackberry (Oliveira et al., 2021) and cape gooseberry (Oliveira et al., 2022), among others. Therefore, our objective was to investigate the relationships between the physical variables of the 'Gala' apple, one of the most produced varieties in Portugal, and to determine their direct and indirect contributions through path analyses.

2. MATERIAL AND METHODS

2.1. Fruit material

Two commercial 'Gala' apple orchards, P1 (producer 1) and P2 (producer 2), located at Alcobaça (western region of mainland Portugal), with different edaphoclimatic conditions, were studied during three years (2018 – 2020) (Figure 1). The orchard soil was classified according to the Portuguese soil chart as clay (P1) and sandy (P2). According to the Köppen and Geiger classification, the region's climate is Csb-type. The average temperature during summer is 20.4 °C. The average annual rainfall is 696 mm, and it is around 15 mm during the summer months.

Four-year-old apple trees were used for the study. Pooled samples of fruits were collected in each orchard each year on the commercial harvest date, typically by the end of August. Six pooled samples of 60 apples each were obtained at harvest during the three-year study.

Figure 1. Apples from producer 1 (P1) and producer 2 (P2) were used in the study, corresponding to the 2018 to 2020 harvest seasons.
Figura 1. Maçãs do produtor 1 (P1) e do produtor 2 (P2) utilizadas no estudo, correspondentes às safras de 2018 a 2020.

2.2. Quality analysis

Immediately after harvest, different quality parameters were evaluated. The mass of each apple was determined with the aid of a digital scale KERN (KERN & SOHN GmbH) and expressed in g. The diameter and height of the fruit were obtained with a digital caliper (Comecta S.A., Spain), the smallest unit 0.01 mm, and the results were expressed in mm.

The volume of the fruit was calculated according to Oliveira et al. (2021), and the result was expressed in cm^3. Pulp firmness was determined in three equidistant equatorial zones of the fruit using a Penefel penetrometer (Setop S.A., France). The results were expressed in kg cm^{-2}.

2.3. Multivariate statistics

Subsequently, the data were subjected to descriptive statistics and the correlation network, and the parameters studied were generated by RBio Software, Bhering (2017). The path analysis used in this work used the GENES Software (Cruz, 2013) to seek an association of the relationships between different variables, excluding possible multicollinearity and achieving its efficiency.

Two path analyses were performed: (a) the first analysis considered apple mass (M) as the main dependent variable (Y), and (b) the second analysis considered the model described in Equation 1:

$$Y = \sum_{n=1}^{\infty}(pnXn) \qquad (1)$$

where: Y is the main dependent variable (M); X1, X2, ..., Xn are the independent explanatory variables; and p1, p2, ..., pn are the path analysis coefficients. The coefficient of determination (R^2) was calculated by Equation 2:

$$R^2 = \mathrm{p1y2} + \mathrm{p2y2} + \cdots . + 2\mathrm{p2yp2nr2n} \qquad (2)$$

Cruz et al. (2013) state that ignoring the effects of multicollinearity can lead to harmful results. To this end, multicollinearity diagnostics should be done to make certain studies feasible. In this regard, the degree of multicollinearity of the X'X matrix was established based on its condition number (NC), the ratio between its largest and smallest eigenvalue (MONTGOMERY et al., 2012). If NC > 1000, multicollinearity is considered severe; and if 100 ≤ NC ≤ 1000, multicollinearity is considered moderate to strong; and NC < 100, multicollinearity is considered weak and poses no problem for the analysis. All statistical analyses were performed with GENES software (CRUZ, 2013).

3. RESULTS

The study focused on assessing the physical attributes of 'Gala' apples and their correlations. Figure 2 shows the Pearson correlation network between apples' physical variables. This modern technique measures Pearson correlation and the intensity and direction of linear relationships. The green lines depict positive correlations, while the red lines signify negative correlations. Line thickness indicates a greater degree of correlation.

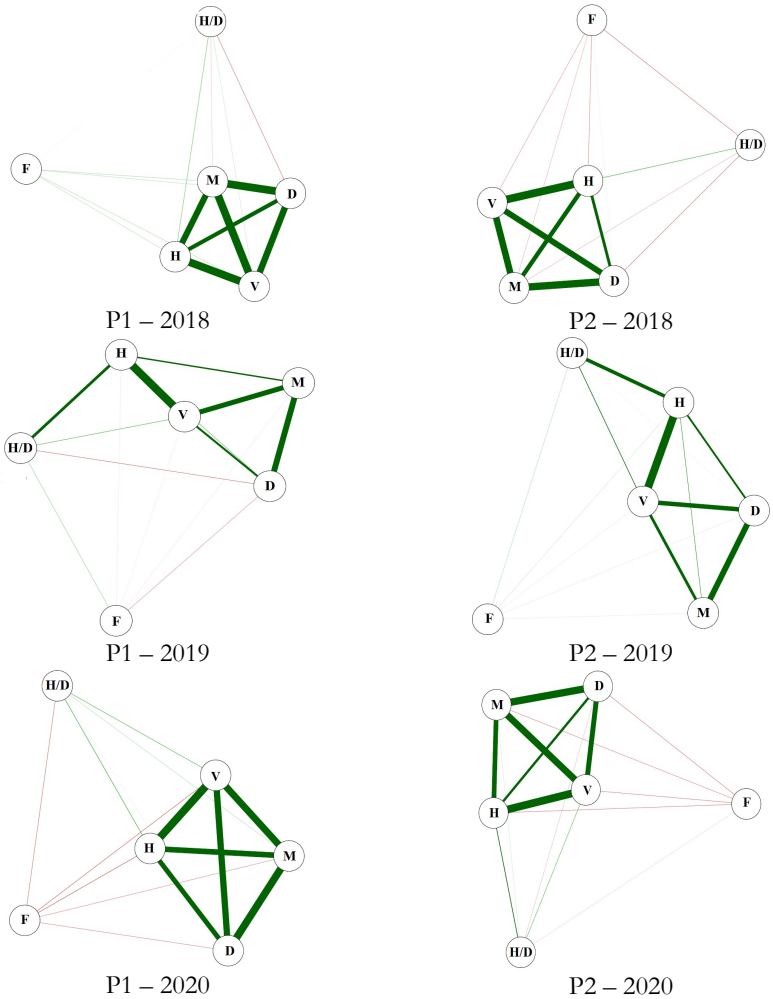

Figure 2. Network of correlations of the physical variables of apples: fruit mass (M), diameter (D), height (H), height to diameter ratio (H/D), volume (V) and firmness (F), for the three harvests (2018, 2019, 2020) and two orchards (P1 and P2).

Figura 2. Rede de correlações das variáveis físicas das maçãs: massa do fruto (M), diâmetro (D), altura (H), relação altura/diâmetro (H/D), volume (V) e firmeza (F), para as três safras (2018, 2019, 2020) e dois pomares (P1 e P2).

Figures 3A and 3B present causal chain diagrams showing the results of the path analysis. Apple mass (M) was considered the main variable of this study, given its significance in determining the income paid to the producer upon sale. The green lines depict positive correlations, while the red lines signify negative correlations. Line thickness indicates a greater degree of correlation.

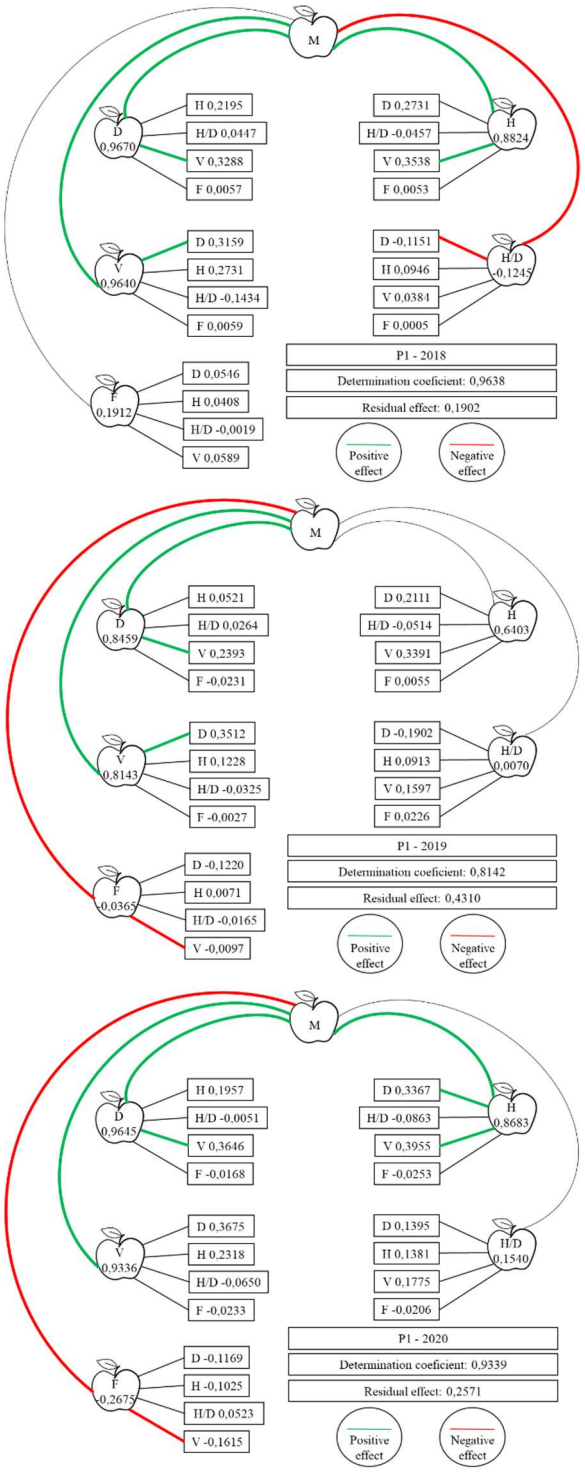

Figure 3A. Path analysis between the physical variables of apples from producer 1 (P1): fruit mass (M), with its primary components, fruit diameter (D), height (H), height to diameter ratio (H/D), volume (V) and firmness (F) performed for the three harvests (P1-2018, P1-2019, P1-2020).

Figura 3A. Análise de trilha entre as variáveis físicas das maçãs do produtor 1 (P1): massa do fruto (M), com seus componentes primários, diâmetro do fruto (D), altura (H), relação altura/diâmetro (H/D), volume (V) e firmeza (F) realizada para as três safras (P1-2018, P1-2019, P1-2020).

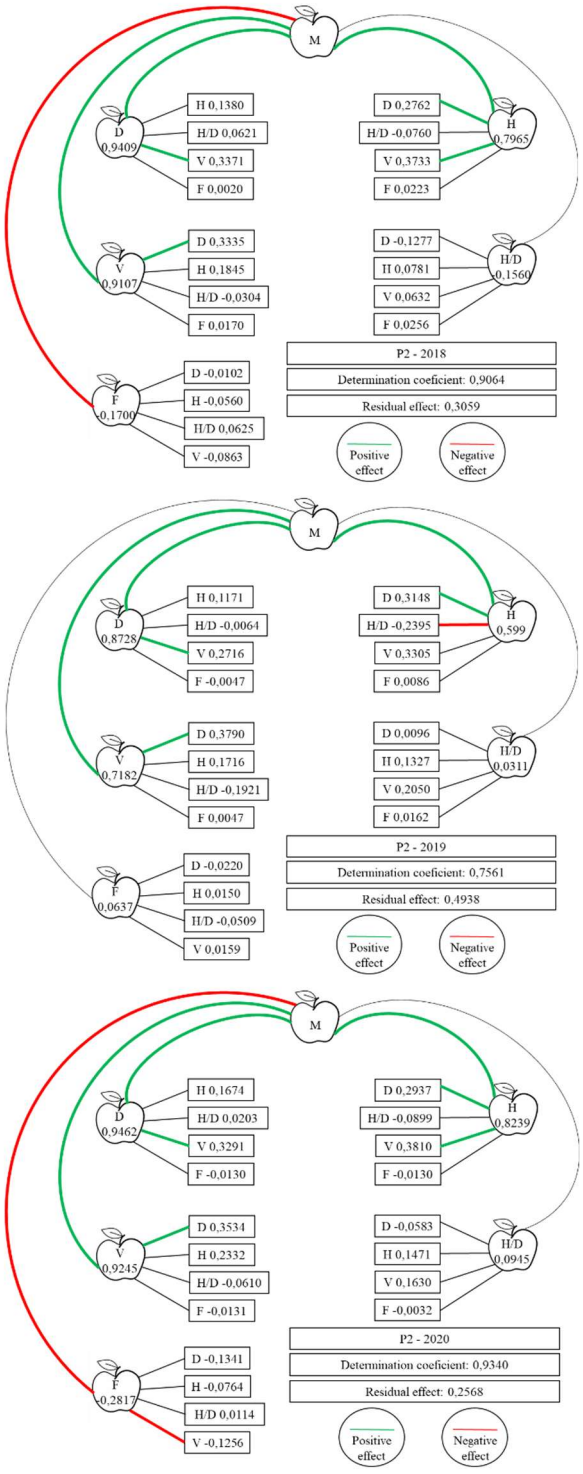

Figure 3B. Path analysis between the physical variables of apples from producer 2 (P2): fruit mass (M), with its primary components, fruit diameter (D), height (H), height to diameter ratio (H/D), volume (V) and firmness (F) performed for the three harvests (P2-2018, P2-2019, P2-2020).

Figura 3B. Análise de trilha entre as variáveis físicas das maçãs do produtor 2 (P2): massa do fruto (M), com seus componentes primários, diâmetro do fruto (D), altura (H), relação altura/diâmetro (H/D), volume (V) e firmeza (F) realizada para as três safras (P2-2018, P2-2019, P2-2020).

4. DISCUSSION

'Gala' apples are red or bicolored, semi-striped fruits with a juicy consistency, sweet taste and excellent gustatory quality. According to APMA (2014), this variety has good conservation properties but lacks caliber over time, resulting in rather heterogeneous harvests. Thus, determining the caliber at the entrance of the cold storage facilities is essential for classifying the fruit and making important decisions, such as the price to be paid to the producer or target markets.

Furthermore, it would be highly desirable to integrate additional parameters into the selection process that better express the quality of the fruit.

Although the orchards are located in the same region, climate variations or different soil types may contribute to subtle differences in the parameters assessed. However, the variables of mass, height, diameter, and volume of the 'Gala' apples exhibited a high and positive correlation. Similar results were found by Farrokhi et al. (2013) in native apples from different geographical regions of Iran. Toebe et al. (2016), when evaluating the quality parameters of 'Royal Gala' and 'Fuji' apples produced in Brazil, observed that the physical aspects of mass, height, diameter and volume also showed high and positive correlations among them.

Assessing apples' morphological and productive traits before or during harvest can contribute to obtaining fruits of superior commercial quality, especially regarding physical and chemical characteristics. Studying existing linear associations between these traits enables the selection or indirect evaluation of attributes of interest, facilitating non-destructive fruit assessments (PALMER et al., 2010; TOEBE et al., 2016).

Paim et al. (2022) studied apple trees and found that the Pearson correlation between fruit load and fresh mass negatively correlated with vegetative growth. However, increases in vegetative growth will not always result in reductions in fruit fresh mass and vice versa, as the existence of a significant correlation does not necessarily imply randomness. This can be exemplified by the influence of various other factors on vegetative and fruit growth, which makes it necessary to carry out additional analyses for this purpose (CHAPLOUTSKYI et al., 2023). Path analysis fits in to present more solid and consistent results between the variables studied without the influence of multicollinearity.

Oliveira et al. (2021) performed path analysis among the physical components of chayote fruit mass. The physical attributes of fruit volume, area, perimeter, and smaller transversal diameter have more potential to select and identify more attractive fruits of the Cambray variety for commercial purposes. Rodrigues et al. (2024) evaluated processing grapes using path analysis and found that the number of clusters per vine showed a higher correlation and direct influence on grapevine fruit production. On the other hand, the number of clusters indirectly influenced the fresh mass of the berries and the length and width of the grapevine production variable.

In Figures 3A and 3B, apple mass (M) was considered the main variable of this study. Teodoro et al. (2014) mentioned that this analysis provides detailed knowledge of the influence of the parameters involved and justifies the existence of positive and negative correlations of high and low magnitude between the parameters studied. Another critical point is that path analysis corrects multicollinearity between attributes, providing reliable results of the relationship between attributes without external interference.

Figure 3A shows the variables directly affecting apple mass in P1-2018, P1-2019 and P1-2020. In all the cases, a direct and positive effect is observed on apple mass, which is strongly influenced by diameter, height, and volume. Santana et al. (2020) found the same results with studies on physalis fruit, highlighting that several biological factors can influence fruit phenology, including pest attack, plant age, availability of nutrients in the soil, and others. However, climate is the main factor affecting phenology during plant cycles and fruit development.

For P1-2018, the relationship H/D influences the mass directly and negatively, and the diameter indirectly and negatively contributes to this effect.

In P1-2019 and P1-2020, apple mass is directly and negatively influenced by firmness; this implies that apples with higher mass have lower firmness, while apples with lower mass have higher firmness. Corroborating the results, Toebe et al. (2016), when evaluating 'Royal Gala' and 'Fuji' apples at harvest, observed that fruits with higher mass had lower pulp firmness and higher total soluble solids content, regardless of cultivar.

Data from P1-2020 (Figure 3A) indicate that volume indirectly negatively influences firmness. The larger the apple's volume, the lower its firmness.

Figure 3B presents the results obtained for P2-2018, P2-2019, and P2-2020, consistent with the previously observed for orchard 1 (P1). Similarly, a direct and positive effect on the mass variable was noted; apple mass is strongly influenced by diameter, height, and volume.

In this case, the mass of the apples in P2-2018 and P2-2020 exhibits a significant negative association with firmness, confirming that the greater the mass, the lower the firmness; conversely, the opposite effect is also evident.

Fruits with greater mass but lower firmness are particularly vulnerable to mechanical damage during transport and storage, potentially compromising quality and limiting shelf life, as previously reported by various authors (JOHNSTON et al., 2002; CHITARRA; CHITARRA, 2005; PRANGE et al., 2011; LEE et al., 2013). . This relationship indicates the need for specific strategies, such as using packaging that minimizes impacts or grading systems that prioritize separating these more sensitive fruits to enhance the value of 'Gala' apples through the short supply chain. In addition, adjustments to handling practices, such as transport at controlled temperatures (ARGENTA et al., 2024) or the use of bioactive coatings (SÁNCHEZ-TAMAYO et al., 2024), can help preserve the quality of fruit with greater volume and lower firmness.

Among the relationships depicted in Figures 3A and 3B, a direct and negative relationship in the parameter of mass and firmness stands out, as well as the direct and positive relationship between mass and diameter and mass and volume. This pattern was consistent across both experimental areas (P1 and P2). The coefficients of determination of the path analysis models R^2 had average values of 0.8847, indicating that the explanatory variables used explain a large part of the variations in the primary variable. All this underscores the importance and usefulness of employing the apple mass for direct and indirect selection of the variables height, diameter, H/D, volume, and firmness of the apples, rather than solely relying on measuring the maximum equatorial diameter currently used for fruit classification.

Even though the general associations may seem predictable, the quantitative validation of these correlations

provides a solid basis for optimizing agricultural and commercial practices.

5. CONCLUSIONS

The analyzed apples exhibited consistent behavior, showing a strong Pearson correlation between their mass and dimensions, such as diameter, height, and volume. This correlation suggests that physical indices hold significant potential for classifying apples based on their characteristics.

Additionally, apples with greater mass and volume tend to have lower firmness, highlighting the need for extra care during handling and transportation to prevent physical and mechanical damage. Therefore, incorporating apple mass for direct and indirect selection of key components through path analysis could enhance the classification systems for 'Gala' apples, enabling a broader evaluation of fruit quality.

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