



## RESEARCH ARTICLE OPEN ACCESS

# Multiparametric Cranberry (*Vaccinium macrocarpon* Ait.) Fruit Textural Trait Development for Harvest and Postharvest Evaluation in Representative Cultivars

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## ABSTRACT

Fruit texture is a priority trait that guarantees the long-term economic sustainability of the cranberry industry through value-added products such as sweetened dried cranberries (SDCs). To develop a standard methodology to measure texture, we conducted a comparative analysis of 22 textural traits using five different methods under both harvest and postharvest conditions in 10 representative cranberry cultivars. A set of textural traits from the 10%-strain compression and puncture methods were identified that differentiate between cultivars primarily based on hardness/stiffness and elasticity properties. The complementary use of both methodologies allowed for a detailed evaluation by capturing the effect of key texture-determining factors such as structure, flesh, and skin. Furthermore, the high effectiveness of this approach in different conditions and its ability to capture high phenotypic variation in cultivars highlights its great potential for applicability in various areas of the value chain and research. Therefore, this study provides an informed reference for unifying future efforts to enhance cranberry fruit texture and quality.

## 1 | Introduction

In recent decades, the cranberry industry has experienced significant growth driven by its appreciation as a functional food (Vorsa et al. 2002; Howell 2009; Vorsa and Zalapa 2019; Zhao, Liu, and Gu 2020). The expansion of the cranberry industry has positively impacted the development and economy of the United States and Canada, which contribute more than 96% of global production (FAOSTAT 2021). In the United States alone, 365,505 tons of cranberries were produced in 2022 with a value greater than \$305 million generated mainly by

its processing industry that traditionally uses around 97% of the national volume (USDA NASS 2022). Although in the early 2000s cranberry production and prices increased constantly, in 2008 prices started to decline, triggering measures to regulate volumes and encouraged diversification of processed products (Gallardo et al. 2018; Kramer, Simnitt, and Calvin 2021). This led to a rapid market shift from cranberry juice to higher value-added products such as sweetened dried cranberries (SDCs). The new target market became popular quickly and from 2010 SDCs were positioned as a new flagship product, desired by both consumers and producers (Vorsa and

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Johnson-Cicalese 2012). However, the exploitation of this new opportunity has been limited due to the demand for cranberry fruit with different and higher quality parameters. Beyond high levels of anthocyanin, the desired fruit characteristics for SDC production include large size, round shape, full flesh, and sufficiently high levels of firmness to allow the fruit to remain as intact as possible during long-term frozen storage, thawing, and subsequent SDC processing (Diaz-Garcia et al. 2019). Thus, more than 20% of annual cranberry tonnage has to go to low value juice concentrate, due to poor fruit quality. This creates two economic issues—the high value SDC market demand cannot be met and returns on juice have reached historic minimum prices (Gallardo et al. 2018). Efforts to address these limitations include a survey of United States and Canadian cranberry stakeholders by Gallardo et al. (2018). Respondents identified the need for cultivars with improved fruit quality, especially firmness/texture, as a priority. In response, cranberry's stakeholders are working in a coordinated manner to overcome the challenges that compromise the economic sustainability of the industry and satisfy the cranberry fruit quality standards required by the changing market.

Despite its importance, the texture of raw and processed cranberries has barely been explored by some studies (Forney 2008; Shamaei, Emam-Djomeh, and Moini 2012; Diaz-Garcia et al. 2019; Zielinska, Markowski, and Zielinska 2019; Liu et al. 2020; Kovacev, Hughes, and Smith 2020; Jamaly, Parent, and Parent 2021; Gorzelany et al. 2022). Furthermore, these reports have used compression, puncture, and shearing methodologies in a variety of contexts and conditions without a common or systematically tested methodology. Therefore, progress in both cranberry firmness research and industry processing practices has been limited as no direct comparison or transfer of results has been possible. This problem is even more critical for cranberry breeding, where an accurate and scalable evaluation method is crucial for different programs to achieve the common goal of producing high quality cranberry cultivars in a coordinated manner. To overcome this challenge, a study was carried out by Lopez-Moreno et al. (2023) to lay the foundation toward the development of an appropriate methodology to measure cranberry firmness. Through the exhaustive analysis of the factors that play a major role in texture evaluation, the study determined the optimal conditions and parameters to carry out the textural measurements in cranberry. Additionally, some textural traits of the compression and puncture methodologies showed promising results to discriminate among cultivars according to their textural properties. This report constitutes, therefore, a key reference for the optimization of texture evaluation for the different purposes of the cranberry industry and has opened opportunities for the development of more specialized methodologies.

In the current study, we further contribute to augment the texture methodologies in cranberry by analyzing the performance of 22 textural traits of 5 different methods under harvest and postharvest conditions in 10 cranberry cultivars that vary in texture. We report the most informative cranberry texture evaluation traits. Additionally, we propose the use of a selected set of traits that represent the best means/indicators for texture evaluation under different conditions. Remarkably, traits of the 10%-strain and puncture compression methods stood out

as the most informative and represent a robust method that allows capturing the contribution of determining factors such as the structure, flesh, and skin of the fruit. This study provides the first systematically tested methodology for texture evaluation in cranberry that will benefit the advancement of the cranberry scientific knowledge to satisfy the industry's fruit quality requirements.

## 2 | Materials and Methods

### 2.1 | Plant Material and Fruit Processing

Ten cultivars with representative cranberry texture phenotypic variation were chosen according to Diaz-Garcia et al. (2019). The cranberry genotypes BG, DP14, DP17, GH1, GR, M34, ST, SUN, V95, and YB are established in individual experimental plots and maintained under conventional crop management conditions at the Valley Corporation cranberry farm in Tomah, WI. The fruit were randomly hand-harvested on September 12, 2018 and sorted. Fruit free of injury or mold were immediately stored at 4°C, except those intended for the freezing test which were stored at -25°C. Prior to testing, the fruit were taken out of storage and left to equilibrate at room temperature (approximately 22°C) for 1 h to avoid measurement bias (Bourne 1982).

### 2.2 | Texture Evaluation

Texture was measured with a Texture Analyzer (TA; XTPlus Connect, Textural Technologies, Hamilton, MA, USA) through five different approaches: 10%-strain compression (C), 50%-strain compression (C50), puncture (P), Shearing (S), and Kramer shear cell (K) (Table 1). Measurements were taken on the equatorial side of each fruit except for Kramer shear cell, which was performed on a 15 g sample. These destructive (C50, P, S, and K) and nondestructive (C) methods were chosen for their ability to capture different texture attributes and their successful implementation in berry-like fruit crops (Slaughter and Rohrbach 1985; Fischer et al. 1992; Blahovec 2001; Silva et al. 2005; Bourne 2002; Maury et al. 2009; Rolle et al. 2012; Giongo et al. 2013). For both compression methods, a 7.62 cm diameter compression plate was used and the tests were conducted with a pre-test speed of 10 mm s<sup>-1</sup>, a test speed of 2 mm s<sup>-1</sup> and a post-test speed of 10 mm s<sup>-1</sup>. These methods differed only in their strain level, one slightly compressing the fruit (10%-strain) while the other was adjusted to fracture the fruit (50%-strain). The puncture method was adjusted to penetrate each berry to a depth of 5 with a 2 mm diameter flat puncture probe and the test was executed with the same speeds as the compression methods. A 45 beveled blade was used to implement the shearing test with a test speed of 8 mm s<sup>-1</sup> and a post-test speed of 15 mm s<sup>-1</sup>. Finally, the Kramer shear cell test was conducted with a 5-blade cell that traveled a distance of 60 mm with test and post-test speeds of 3 and 10 mm s<sup>-1</sup>, respectively. The textural traits generated by these methods are summarized in Table 1 and were derived from the force deformation curve or according to previous reports as indicated below. 10%-strain compression traits were calculated from the force/distance, force/strain, force/time, and stress/strain profiles following previous reports (Grotte et al. 2001; Maury

**TABLE 1** | List of traits generated by five texture methodologies evaluated in cranberry fruit (*Vaccinium macrocarpon* Ait.).

Texture trait	Acronym	Unit	Description
Puncture			
Apparent modulus of elasticity	P_AMOE	Pa	The slope of the force/distance curve divided by the surface area of the probe's end
Maximum force	P_Max	N	The highest force recorded during the test
Deformation at rupture	P_DR	mm	The distance the probe travels between the first contact and the highest force
Work	P_W	mJ	The area under the force/distance curve up until rupture
Shearing			
Maximum force	S_Max	N	The highest force recorded during the test
Deformation at fracture	S_DF	mm	The distance the probe travels between the first contact and the highest force
Work	S_W	mJ	The area under the force/distance curve
Kramer shear cell			
Max force	K_Max	N	The highest force measured during the test
Work	K_W	mJ	The area under the entire force/distance graph
50%-strain compression			
Rupture force	C50_RF	N	The force needed to rupture the berry
Rupture distance	C50_RD	mm	The distance the fruit was compressed before rupture
10%-strain compression			
Maximum force	C_h1	N	The highest force recorded during the first compression
Force/distance slope	C_dsf1	N/mm	The slope of the force/distance curve for the first compression
Force/distance area	C_dW1	mJ	The area under the force/distance curve for the first compression
Force/strain slope	C_Sf1	N	The slope of the force/strain curve for the first compression
Force/strain area	C_W1	N	The area under the force/strain curve for the first compression
Maximum stress	C_pr1	Pa	The highest stress recorded during the first compression
Stress/strain area	C_A1	Pa	The area under the stress/strain curve for the first compression
Force/time slope	C_tsf1	N/s	The slope of the force/time curve for the first compression
Force/time area	C_tW1	Ns	The area under the force/time curve for the first compression
Maximum contact pressure	C_MCP	Pa	The maximum contact pressure calculated for the first compression
Apparent modulus of elasticity	C_AMOE	Pa	The slope of the force/distance curve divided by the surface area of the probe's end

et al. 2009; Diaz-Garcia et al. 2019; Giongo et al. 2022; Lopez-Moreno et al. 2023). For this method, maximum contact force and apparent modulus of elasticity were also calculated as has been suggested for convex shape commodities (Johnson 1985; ASAE 2000). On the other hand, the traits for 50%-strain compression, puncture, shearing, and Kramer shear cell were calculated from the force/distance profile. Furthermore, puncture traits were complemented with apparent modulus of elasticity (ASAE 2000).

### 2.3 | Harvest Evaluation

All samples were run on 100 fruit of each cultivar, except Kramer shear cell, which used 15 samples of 15 g for each cultivar. These measurements were made around the first month of storage since the textural properties of cranberry remain constant during this period (Bourne 1979; Forney 2008; Lopez-Moreno et al. 2023). Measurements were made at 31, 33, 35, 38, and 39 days for 10%-strain compression, 50%-strain compression, Kramer shear cell, puncture and shearing, respectively.

### 2.4 | Postharvest Evaluation

Based on the preliminary results of the harvest test and its effectiveness for most crops, the postharvest test focused only on the 10%-strain and puncture methods. Hundred fruits of each cultivar were evaluated on four storage dates with both methods, with measurement at harvest designated as the first measurement. This equates to 31, 86, 163, and 288 days of storage for the 10%-strain method and 38, 79, 167, and 282 days of storage for the puncture method. Cultivars DP14 and DP17 were evaluated only in the first three dates due to the limited number of fruit available.

### 2.5 | Evaluation on Thawed Fruit

Puncture and 10%-strain compression were further evaluated with thawed fruit. After 60 days of storage at  $-25^{\circ}\text{C}$ , all fruit frozen samples were thawed to room temperature. Before taking the measurements, we made sure that the fruit were completely thawed to avoid the presence of ice pieces. Texture measurements were carried out as described above and were finally compared with the values obtained at harvest.

### 2.6 | Data Processing and Statistical Analysis

Texture data calculation and statistical analysis were performed with custom R software scripts (R Core Team 2023). Principal component analysis (PCA) was implemented as a dimension reduction and variable selection method (Nguyen and Holmes 2019). This analysis was implemented with the average of the 100 fruit of each observation. The selection of variables was based on their projection, their contribution to the dimensions that explained the greatest percentage of variation, as well as for its affinity to capture certain texture attributes. Basic descriptive statistics, Pearson's correlation, Dunn's test, and generalized least squares were computed as reported. Additionally, the storage

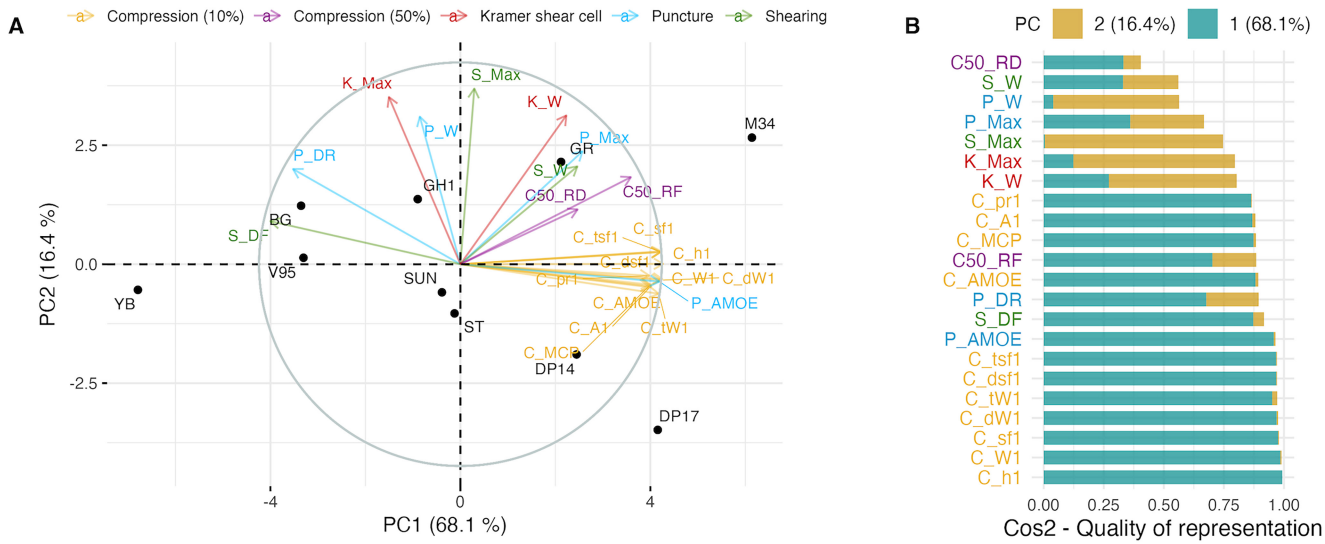
index (SI) was calculated with the following formula:  $\text{SI} = \log_2(\text{Ti2M}/\text{Ti H})$ , where Ti H is the value of the "i" texture parameter measured at harvest, and Ti2M is the value of the same parameter on the second evaluation date (Costa et al. 2012).

## 3 | Results and Discussion

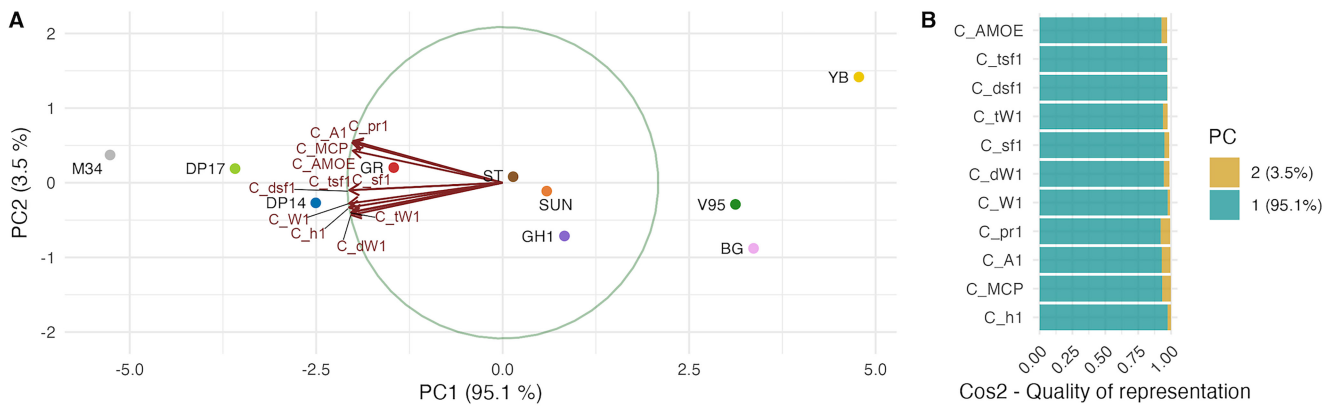
### 3.1 | Comparison of Multiple Textural Traits at Harvest

A PCA was carried out using 22 textural traits from five different methods to identify the most discriminating attributes between cultivars (Figure 1). Most of the texture variation was captured by PC1 and PC2 (>84%), which allowed a clear differentiation of cultivars as they spread out in the four PCA quadrants (Figure 1A). PC1 explained the greatest variation with >68%, supported mainly by the nondestructive 10%-strain compression method associated with hardness. In contrast, PC2 only explained around 16% of the variation, supported mainly by destructive methods, predominant by characteristics of elasticity and resistance to rupture. Based on the contribution, the compression traits (10%-strain) were the most relevant cranberry textural traits followed by puncture traits (Figure 1B). These two methodologies are widely used in a complementary manner in cranberry-like fruit species such as tomato (Li and Thomas 2015), blueberry (Giongo et al. 2022; Rivera et al. 2021; Rivera et al. 2022; Rivera et al. 2023), and grape (Maury et al. 2009; Río Segade et al. 2011; Rolle et al. 2012), since they allow a comprehensive characterization of the mechanical characteristics. In both methods, the influence of the pericarp and skin are aggregated, but the pulp is more accurately assessed by compression, while puncture is the preferred method when the test focuses on the skin (Bares et al. 1994; Rolle et al. 2012; Rosenthal, Lacsse, and Voyer 2018). In particular, the predominance of 10%-strain compression may be attributed to its reliance on the collective response of the fruit anatomy and tissues, which must be determining factors of the texture. This observation has been reported in fruit with similar locular anatomy, such as tomato (Li et al. 2012, 2013; Li and Thomas 2015).

To filter out the most reliable and effective traits, the analysis was narrowed down to the most informative methods, 10%-strain compression and puncture (Figures 2 and 3). The PCA for 10%-strain compression showed that PC1 explains most of the variation (95.1%) and that the traits are redundant due to their very similar projection with only a slight differentiation of some traits that account for berry size (C\_AMOE, C\_MCP). Of the 11 traits of 10%-strain compression, the apparent modulus of elasticity (C\_AMOE), maximum contact pressure (C\_MCP), and maximum force (C\_h1) stand out as the best candidates to reliably determine cranberry texture since they capture much of the variation and cover the two projection clusters of the traits observed in the PCA. These three compression traits had a wide range of variation and detected significant differences in this set of cultivars (Dunn's test,  $p < 0.05$ ) (Table S1). C\_h1 has been widely used in cranberry as the simplest approach to measuring firmness based on a single data point (Forney 2008; Jamaly, Parent, and Parent 2021; Diaz-Garcia et al. 2019). Meanwhile, C\_MCP and C\_AMOE have been less explored (Gorzalany et al. 2022; Lopez-Moreno et al. 2023), but these traits designed specifically for the



**FIGURE 1** | Principal component analysis (PCA) based on average data from 10 cranberry (*Vaccinium macrocarpon* Ait.) cultivars evaluated at harvest with five texture methodologies. (A) Distribution of cultivars and projection of variables (textural traits) for PC1 and PC2. (B) Ranking of the contribution of textural traits to PC1 and PC2. Textural traits labels are colored based on their methodology.



**FIGURE 2** | Principal component analysis (PCA) based on average data from 10 cranberry (*Vaccinium macrocarpon* Ait.) cultivars evaluated at harvest with the 10%-strain compression method. (A) Distribution of cultivars and projection of textural traits for PC1 and PC2. (B) Ranking of the contribution of textural traits to PC1 and PC2.

evaluation of convex commodities (Johnson 1985; ASAE 2000). Thus, the relevance of C\_h1, C\_MCP, and C\_AMOE indicates that the cultivars are differentiated mainly by their hardness/stiffness. The slight variation between the traits that do and do not consider the fruit size has been reported by Lopez-Moreno et al. 2023 and it is thought that it may compromise the effectiveness of texture evaluation to discriminate between cultivars. To determine the adequate usefulness of C\_h1, C\_MCP, and C\_AMOE, more analysis will be necessary to establish their relationship with other fruit characteristics, their reliability for more detailed analyzes such as genetic mapping, as well as their applicability for industrial processes.

On the other hand, puncture traits captured a greater variety of attributes, since the explained variation was more distributed among the PCs and the projection of the variables was less redundant. The distribution of the cultivars on PC1 was similar to that of the compression method but different for PC2, particularly for the M34 cultivar, which differed markedly. P\_DR and P\_MAX were the most useful traits to discriminate between cultivars due

to their high contribution to PC1 and PC2, which explained 53.9% and 45.8%, respectively. The P\_DR differentiated cultivars according to elasticity, ranging from 1.47 mm for DP17 to 2.34 mm for YB (Table S2). In blueberry, this texture characteristic has been associated with fruit turgidity, so cultivars with greater elasticity should have less turgid fruit and vice versa (Giongo et al. 2022). Although P\_MAX also had high variation, the main differentiation was between M34 and the rest of the cultivars. Therefore, the usefulness of P\_MAX could vary depending on the set of cultivars evaluated. Experiments with spherical model fruits have revealed that P\_MAX is impacted by the skin, thus offering a dependable way to account for this fruit component (Rosenthal, Lacresse, and Voyer 2018). Because P\_MAX is related to pericarp's resistance to damage, cultivars with high P\_MAX values may have better performance during handling and storage.

The complement of compression and puncture traits represent a robust means for the evaluation of texture in cranberry fruit at the time of harvest, since they capture the influence of the structure, flesh, and skin of the fruit. Although the puncture

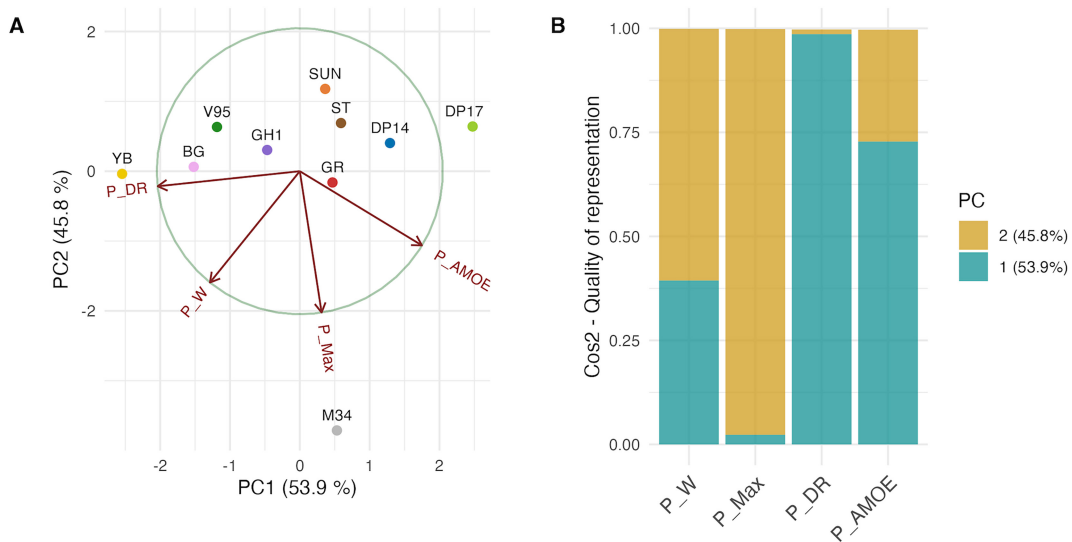
method (2 mm flat probe) provided favorable results, its effectiveness could be surpassed with the use of needle probe and may potentially be the ideal method for measuring the skin (Giongo et al. 2022). The use of both methods is recommended for a complete evaluation, and under the optimal conditions (Lopez-Moreno et al. 2023). As such, we encourage the adoption of compression (C\_h1, C\_MCP, and C\_AMOE) and puncture traits (P\_DR and P\_MAX) for texture evaluation at harvest by cranberry stakeholders to consolidate a standard methodology that will facilitate communication and reproducibility of results.

### 3.2 | Comparison of Multiple Textural Traits in Postharvest Storage

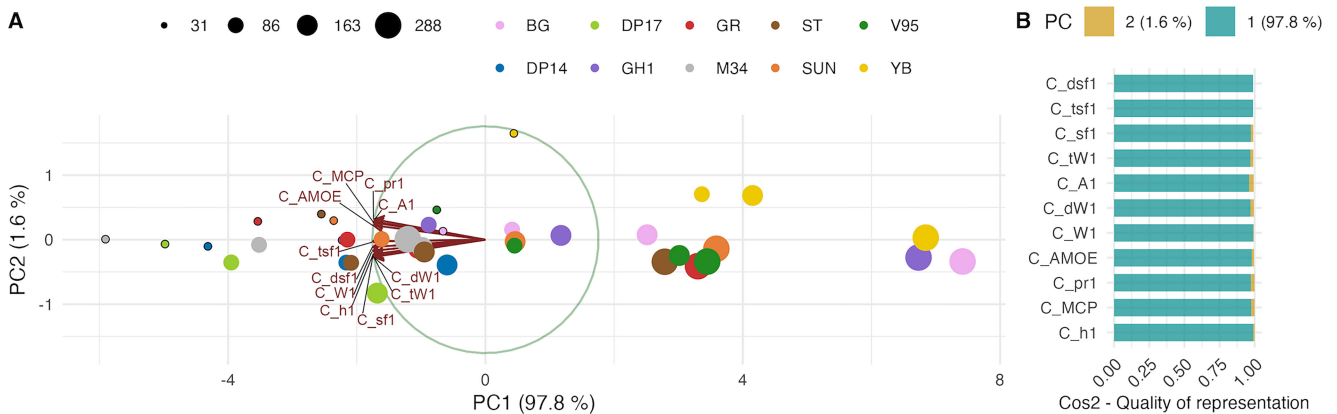
To develop a reliable method to evaluate the performance of cranberry genotypes during storage, the compression (10%-strain) and puncture methods were also evaluated under prolonged

storage conditions (Figures 4 and 5). The tests focused on these methods due to their outstanding performance in discriminating among cultivars at harvest. In general, both methods clearly separated between cultivars and dates. Furthermore, the results obtained at harvest were reproducible between and within the methods when evaluated during storage. The compression method (10%-strain) continued to stand out due to the large variation captured by the first dimension alone (97.8%), although the first two puncture PCs also captured a high variation (97.7%). The results within the methodologies were similar to those obtained at harvest in terms of the importance of the PCs, and the projection of both the traits and the cultivars. Similar observations have been reported for anatomically varied fruit such as blueberry (Giongo et al. 2013) and apple (Costa et al. 2012), which can be attributed to the robustness of the evaluation method.

For 10%-strain compression, C\_h1, C\_AMOE, and C\_MCP remained the most informative traits. Conversely, the puncture



**FIGURE 3** | Principal component analysis (PCA) based on average data from 10 cranberry (*Vaccinium macrocarpon* Ait.) cultivars evaluated at harvest with the puncture method. (A) Distribution of cultivars and projection of textural traits for PC1 and PC2. (B) Ranking of the contribution of textural traits to PC1 and PC2.

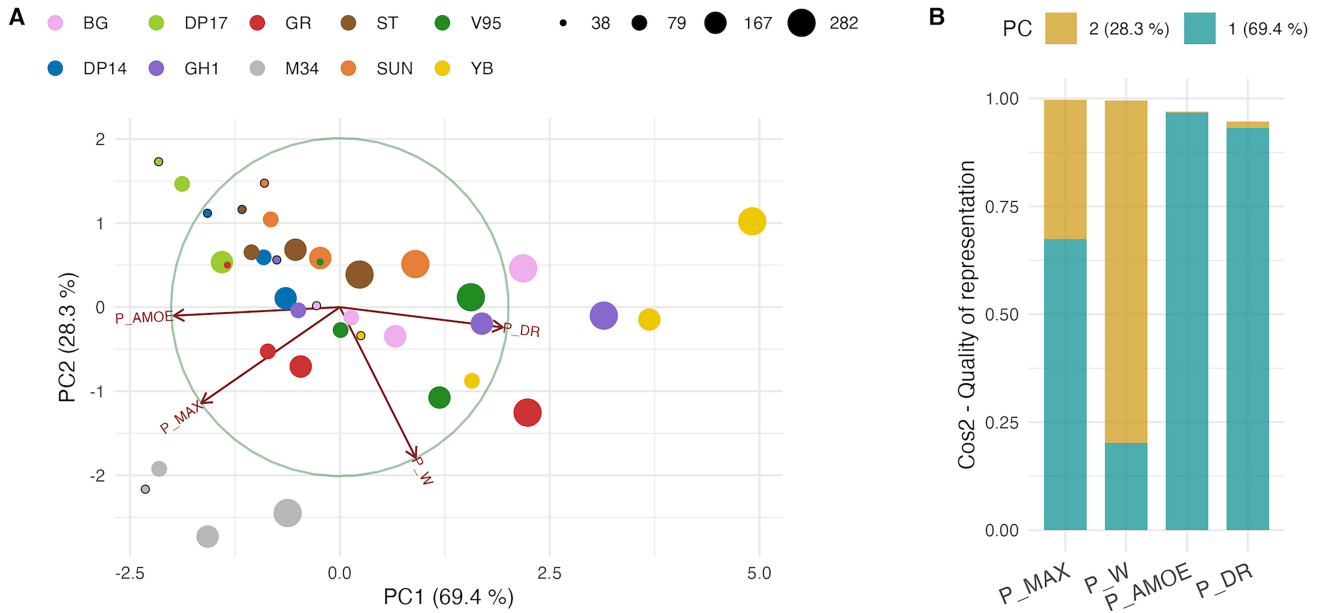


**FIGURE 4** | Principal component analysis (PCA) based on average data from 10 cranberry (*Vaccinium macrocarpon* Ait.) cultivars evaluated at four periods of storage with the 10%-strain compression method. (A) Distribution of cultivars-storage time points and projection of textural traits for PC1 and PC2. (B) Ranking of the contribution of textural traits to PC1 and PC2. Every point is colored according to a cultivar and its size proportionally corresponds to the storage time.

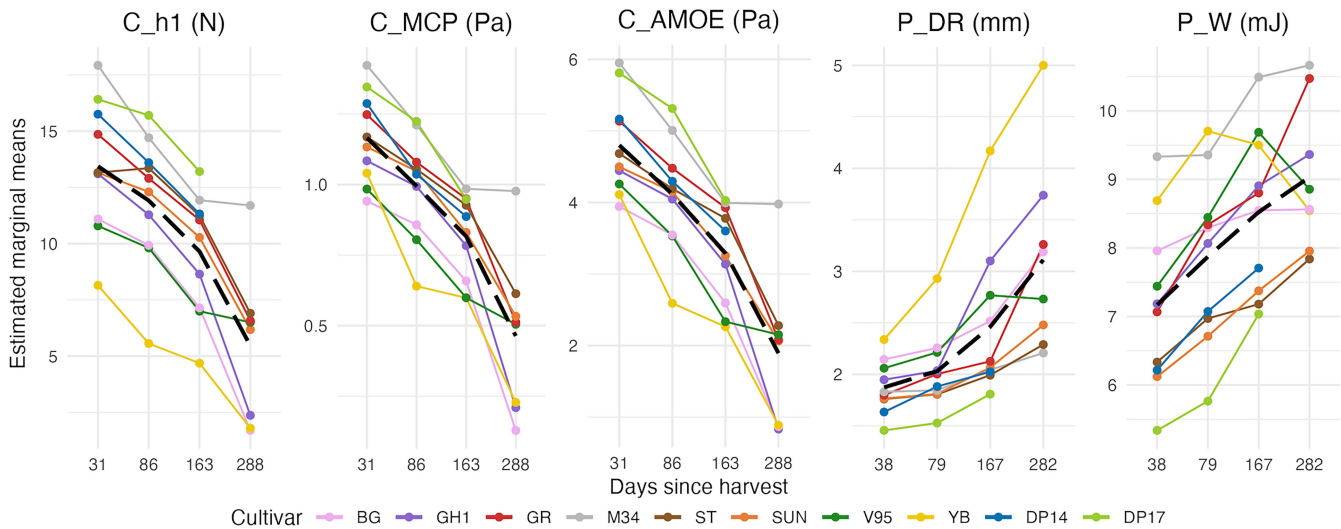
method showed some interesting differences. The P\_DR maintained a high contribution to PC1 during the storage test as at harvest, while P\_W became more relevant for PC2 in contrast to the harvest test where P\_MAX was predominant. The loss of relevance of P\_MAX can be explained by the gradual decrease in resistance of the fruit structure which is necessary for the fruit to be penetrated. This result suggests that, at least with the flat-probe puncture method used here, the texture behavior in storage is primarily determined by the anatomy and flesh of the fruit rather than the skin. However, the puncture method should be reevaluated with needle probes that allow better capturing the role of the skin in storage conditions.

### 3.3 | Monitoring Texture Dynamics During Storage

Based on the most informative traits, cultivar had a clear and significant effect on the behavior of the fruit during storage (Figure 6, Table S3). For compression traits, the results were similar and showed that texture decreases over time with different intensity depending on the cultivar. Despite the fluctuations, the rate of decrease in firmness was mostly constant for all cultivars, and hence their ranking is maintained throughout storage as previously reported for this crop (Lopez-Moreno et al. 2023). The cultivars showed a varied response during



**FIGURE 5** | Principal component analysis (PCA) based on average data from 10 cranberry (*Vaccinium macrocarpon* Ait.) cultivars evaluated at four periods of storage with the puncture method. (A) Distribution of cultivars-storage time points and projection of textural traits for PC1 and PC2. (B) Ranking of the contribution of textural traits to PC1 and PC2. Every point is colored according to a cultivar and its size proportionally corresponds to the storage time.

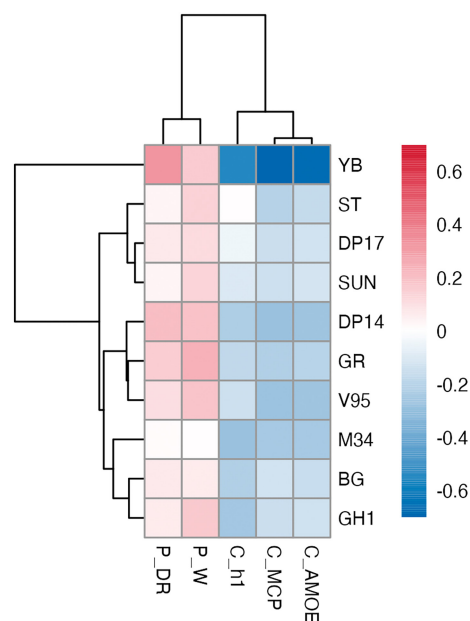


**FIGURE 6** | Storage dynamics of fruit texture of 10 cranberry (*Vaccinium macrocarpon* Ait.) cultivars through prolonged storage at 4°C based on C\_h1, C\_AMOE, C\_MCP, P\_DR, and P\_W traits. Estimated marginal means obtained from the generalized least squares model are plotted at each point.

storage which was more evident for C\_h1. For this trait, some cultivars such as M34, DP14, and DP17 (17.76, 15.93, and 16.53 N, respectively), had higher firmness values at the end of storage than the initial firmness values of softer cultivars such as YB, V95, and BG (8.15, 10.80, and 10.99 N, respectively), which highlights the high phenotypic variation in firmness captured (Table S3).

Puncture traits, however, showed increase over time and displayed a similar ranking to compression method although in the reverse direction. For these traits, the differentiation was more evident with deformation at rupture (P\_DR), which has been widely validated in blueberry (Rivera et al. 2021, 2022). According to this trait, the difference between cultivars was more subtle at the beginning and became more differentiated over time, which can be attributed to the fact that the cultivars experience more diverse changes for this characteristic during storage. In particular, YB cultivar had the most distinctive behavior by showing higher values at all measurement times and an accelerated increase in fruit deformation. For P\_W, results were slightly contrasting with the rest of the traits in terms of trends and cultivar rankings. Less defined profiles (more overlaps) and some irregular trends resulted possibly from the lower effectiveness of this trait. Additionally, the measurement of a different texture attribute may be the cause of differences in the cultivars ranking. The five traits evaluated can generate informative storage profiles that can guide decision-making in the management of cranberry fruit, especially when used in a complementary manner. Furthermore, these profiles are characterized by a special long storage life contrasting with the rest of the major berry crops as has been demonstrated before (Bourne 1979; Ruse et al. 2013; Lopez-Moreno et al. 2023). These special characteristics of cranberry may be of interest particularly for hybridization efforts between related species of the *Vaccinium* genus (Ehlenfeldt and Martin 2002; Vorsa, Johnson-Cicalese, and Polashock 2009; Ehlenfeldt et al. 2023).

To quantify the texture change during the first ~8 weeks of storage, the SI was calculated following Costa et al. (2012) in Figure 7 and Table S4. Positive values correspond to enhancement in a texture property, while negative values indicate a loss of performance. This index has been implemented in several species and represents an objective means for comparing the texture dynamics during storage in anatomically diverse fruit (Costa et al. 2012; Giongo et al. 2019, 2022). Compression traits exhibited a negative dynamic as the fruit became soft due to deterioration in storage. On the contrary, SI increased for fruit deformation (P\_DR) and P\_W due to the loss of resistance of the fruit to the force exerted. When evaluating the dynamics of the cultivars, they showed a varied response and were divided into four main groups. Nine of the ten cultivars were clustered in groups of three with similar dynamics, with YB being the only one that stood out from the rest by exhibiting poor storability. In particular, the group of cultivars composed of ST, DP17, and SUN showed good aptitude since their texture properties remained stable during this period. As expected, the traits mainly separated according to their methodology. Furthermore, the traits C\_MCP and C\_AMOE showed the greatest magnitude of change, indicating that they

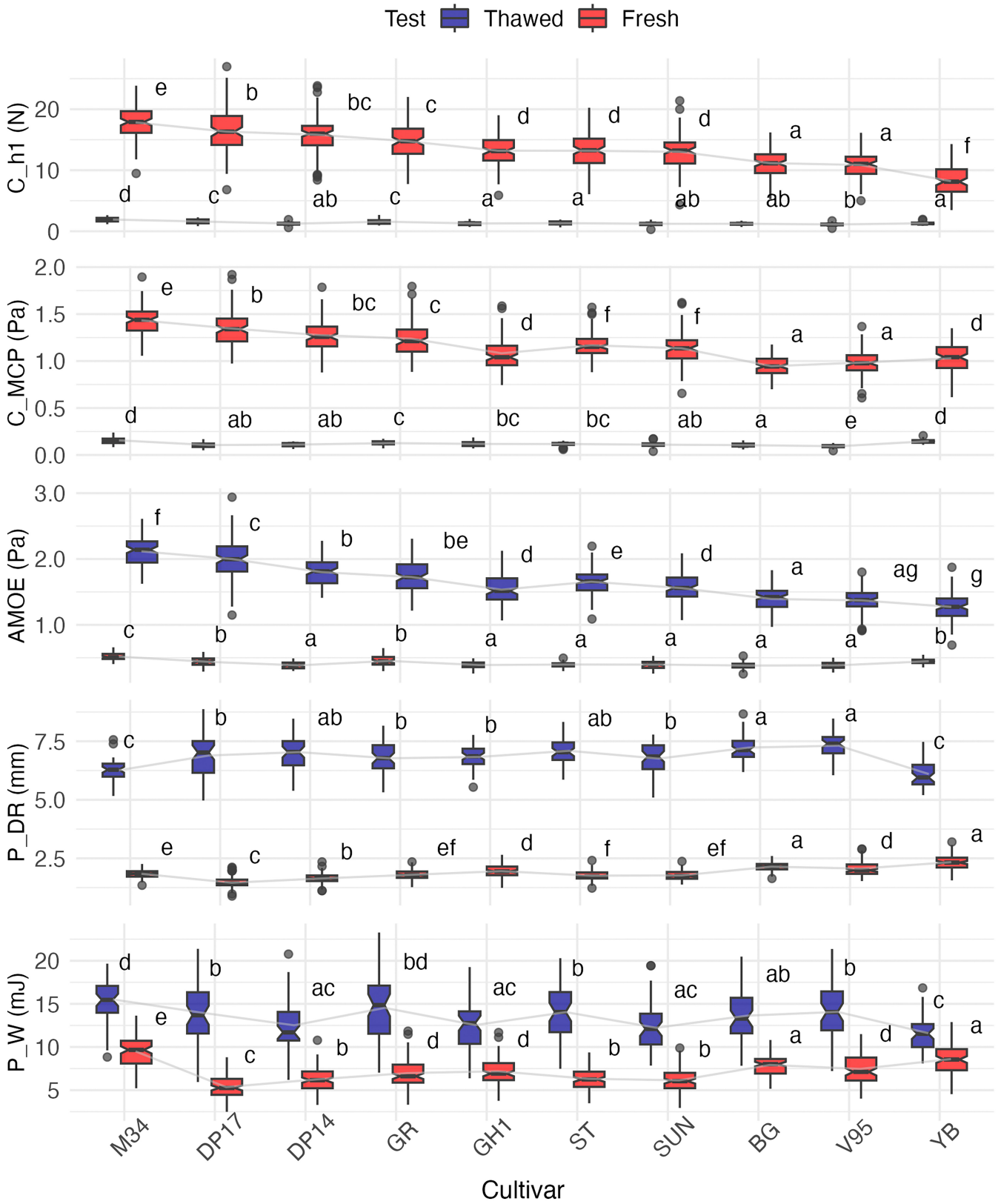


**FIGURE 7** | Heatmap of the storage indices of the traits C\_h1, C\_AMOE, C\_MCP, P\_DR, and P\_W calculated with data from 10 cranberry (*Vaccinium macrocarpon* Ait.) cultivars.

are more sensitive compared to the rest (Table S4). Together with storage profiles (Figure 6), SI can help improve postharvest practices as a reference for specific cultivar fitness during storage.

### 3.4 | Evaluation of the Performance of Candidate Textural Traits in Thawed Fruit

Commercially, cranberry can be stored both refrigerated (~4°C) and frozen (<0°C), so the usefulness of texture measurement must be evaluated under both conditions. The effectiveness of the most informative traits during refrigerated storage was evaluated with thawed fruit that were kept at -25°C for 60 days (Figure 8). When comparing the results of both conditions, large magnitude changes were observed for all traits. Thawed fruit showed a very similar average decrease among compression traits, 89.5%, 89.6%, and 89.9% for C\_h1, C\_MCP, and C\_AMOE, respectively. In contrast, P\_W and P\_DR had an average increase of up to 92.6% and 270.5%, respectively. The drastic deterioration of texture properties due to freezing has been previously reported for cranberry (Diaz-Garcia et al. 2019) and, like other fruit, can be attributed to the physiological breakdown caused mainly by cellular damage due to the formation of ice crystals (Forney 2003; Bonat Celli, Ghanem, and Su-Ling Brooks 2016; Zielinska, Markowski, and Zielinska 2019). For C\_h1, there was a Pearson's correlation of 0.72 ( $p < 0.05$ ) between both conditions although fewer significant differences were detected (Dunn's test,  $p < 0.05$ ) between cultivars with thawed fruit. Conversely, there were no significant correlations between both conditions for the rest of the traits. These results suggest that, although the fruit suffered damage from freezing, the structure of the berry partially maintained its hardness that differentiates between cultivars.



**FIGURE 8** | Boxplot comparing the texture values of the traits C<sub>h1</sub>, C<sub>MCP</sub>, C<sub>AMOE</sub>, P<sub>DR</sub>, and P<sub>W</sub> under fresh and freeze–thaw conditions of fruit of 10 cranberry (*Vaccinium macrocarpon* Ait.) cultivars. Significant differences between cultivars are indicated with different letters (Dunn’s test,  $p < 0.05$ ).

## 4 | Conclusion

Texture is a priority trait for cranberry breeding due to its implications for fruit handling and the growing processing industry. To develop the reliable texture methodologies for this crop, we carried out a comprehensive and comparative study of the methodologies commonly used in fruit for harvest and postharvest. The results showed that the hardness/stiffness characteristics captured by the traits  $C_{h1}$ ,  $C_{MCP}$ , and  $C_{AMOE}$  of the 10%-strain compression method are reliable discriminators of the cultivars in harvest and postharvest.  $C_{h1}$  also partially maintained its performance with thawed fruit, demonstrating the relevance of structure and flesh in determining the texture of cranberry fruit. Regarding the puncture method, some traits such as  $P_W$ ,  $P_{DR}$ , and  $P_{Max}$  were identified as a reasonable texture indicator and are of special interest to capture the skin effect. However, we anticipate that by implementing needle probe puncture in future investigations could refine this method. These results suggest that, as in other crops, the complementary use of both methodologies will allow detailed and informative texture evaluation. The textural traits that we propose represent effective methods for evaluating cranberry texture due to their robustness and the fact that they can capture the wide phenotypic variation present in the evaluated accessions. These resources will benefit the advancement of the cranberry industry through their implementation for research and commercial purposes. However, future research should address the usefulness of these measurements to predict the performance of cultivars at different stages of the production chain, as reported in other species (Slaughter and Rohrbach 1985; Letaief, Rolle, and Gerbi 2008; Rolle et al. 2008; Rivera et al. 2022). Finally, we highlight that the collective use of these resources by the cranberry community will enhance our efforts in different areas and facilitate communication among stakeholders.

### Author Contributions

**Hector Lopez-Moreno:** methodology, software, formal analysis, investigation, validation, data curation, writing – original draft, writing – review and editing, visualization. **Matthew Phillips:** methodology, formal analysis, investigation. **Luis Diaz-Garcia:** conceptualization, methodology, writing – review and editing. **Maria Torres-Meraz:** software, validation, investigation, writing – review and editing, visualization. **Diego Jarquin:** formal analysis, writing – review and editing. **Jenyne Loarca:** validation, writing – review and editing. **Shinya Ikeda:** resources, writing – review and editing, project administration. **Lara Giongo:** writing – review and editing, funding acquisition. **Edward Grygleski:** resources. **Massimo Iorizzo:** conceptualization, writing – review and editing, project administration, funding acquisition. **Juan Zalapa:** conceptualization, resources, writing – review and editing, supervision, project administration, funding acquisition.

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### Ethics Statement

This study does not involve any human or animal testing.

### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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### Supporting Information

Additional supporting information can be found online in the Supporting Information section.