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Review

Blueberry firmness - A review of the textural and mechanical properties used in quality evaluations

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ABSTRACT

Firmness is an important parameter for fresh blueberries as it influences the quality perceived by consumers and postharvest storage potential. However, the blueberry research community has not yet identified a universal standard method that can evaluate firmness for quality purposes. Different mechanical tests have been considered, offering different perspectives on this quality trait. This review summarises the most common methods previously used to evaluate textural and mechanical properties of fresh blueberries as influenced by pre- and postharvest factors. In addition, this review intends to assist the blueberry research community and commercial supply chain when selecting suitable methods to measure blueberry firmness as a fruit quality response. Different research initiatives to develop, optimize or standardise instrumental methods to assess blueberry firmness and relate to consumer sensory perception are reviewed. Mechanical parameters obtained by compression tests are the most previously used techniques to evaluate the influence of genotype, maturity, calcium, and postharvest management on blueberry firmness or to relate to sensory descriptors. However, standardising operational settings (e.g., compression distance, loading speed, and calculation procedures) is required to make results comparable across data collection conditions. Whether other mechanical test methods such as penetration or a combination of tests can better characterise blueberry quality or the relationship with consumer acceptance remains unknown and is worth studying.

1. Introduction

Fruit firmness in plant science is often referred to as the textural or mechanical attributes that can denote differences in the fruit maturity or quality of horticultural commodities (Timm et al., 1996; Abbott, 1999; Lu and Abbott, 2004; Musacchi and Serra, 2018). As a result, fruit firmness can have variable descriptions or interpretations depending on the textural or mechanical evaluation protocols. For most fruit commodities, firmness is referred to as the force (measured in Newtons, N) required to penetrate a fruit using a non-deformable probe (Lu and Abbott, 2004). However, this definition applies universally to firm flesh fruit such as apples, kiwifruit, and peaches. In the case of small soft berries, firmness is often evaluated based on the deformation of the berry when applying a fixed load (Lu and Abbott, 2004).

Several methodologies have been reported to evaluate blueberry firmness. These vary from simple sensory methods, such as squeezing or rolling a blueberry between thumb and index fingers (Sanford et al., 1991; Miller et al., 1993; Nunes et al., 2004; Rodriguez and Zoffoli, 2016), to sophisticated mechanical methods such as the compression test, which requires the use of automatic equipment such as a texture analyser or Instron universal testing machine (Donahue and Work, 1998; Chiabrando et al., 2009; Giongo et al., 2013; Rivera et al., 2021a). Several factors drive the decision of which method or instrumental test (e.g., penetration or compression test) to use when a research experiment is designed. A relevant factor is the availability of the testing machine (e.g., texture analyser, FirmTech 2) and type of probe (e.g.,

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compression plates, needle probe), and how easy it is to implement and conduct the test and analyse the data..

Among the factors influencing blueberry firmness, genotype, maturity, calcium management, and postharvest storage conditions have been identified as the most relevant. However, different methods have been used to characterise the effect of pre- and postharvest factors on textural quality. To further understand and compare the impact of these factors, it is essential to standardise the quality evaluation methods. During the history of research studies on blueberries, different studies have contributed to providing insights that can assist the development of a firmness standard.

Blueberry quality and storage potential can be affected by bruising damage (i.e., flesh browning) induced by machine harvesting or impact damage when dropped in a packing line (Ballinger et al., 1973; Sanford et al., 1991; Xu et al., 2015; Moggia et al., 2017). However, the advanced requirements for mechanical methods to model the mechanical damage resistance of blueberries are beyond the scope of this literature review.

This literature review will summarise:

(1) The methodologies previously used to assess fresh blueberry textural quality and instrumental mechanical parameters.
(2) The pre- and postharvest factors which most affect blueberry texture and mechanical parameters.
(3) The history and state of the art on the development and optimisation of mechanical methods to evaluate firmness and consumer preferences of blueberry.

The authors hope that this review will offer readers a comprehensive summary of the research in this field to date and help the blueberry community to adopt suitable methods to measure blueberry firmness as a quality parameter for different purposes (breeding, pre and post-harvest treatment evaluations, and commercial quality assessment). In addition, this review contributes to assisting the establishment of a universal methodological standard for measuring blueberry firmness.

2. Methods to evaluate blueberry firmness

In food science, the terms “texture” and “material properties” have different meanings and should not be used interchangeably. Texture relates to sensorial descriptors of structural, mechanical, and surface properties of food when perceived by a human when consuming (chewing, touching, and hearing) food such as fruit (Szczesniak, 2002; Kemp et al., 2009). In comparison, mechanical properties are related to parameters measured by an instrumental machine, which generally records food sample changes in shape or size when an external loading (force) is applied (Szczesniak, 1963). Hereafter, terms related to “texture” will be used when referring to sensory perception by a human subject, and “mechanical or material” attributes will be used to denote the parameters assessed by an instrumental device and calculated by a specific physical model (Chen, 2020).

This section will summarise sensory and instrumental mechanical methods used to characterise firmness as a blueberry quality response. The most used instrumental mechanical methods in blueberry research studies, such as uniaxial compression, penetration, and texture profile analysis, will be described based on probes used to conduct the tests and mechanical parameters that each mechanical test can measure. In addition, we present strengths, weaknesses, and recommendations for different instrumental used to characterise the mechanical parameters of blueberry for research or commercial purposes. Finally, studies exploring the use of true non-destructive techniques that can be used to predict/evaluate mechanical parameters of blueberry are reviewed.

2.1. Sensory methods

Sensory analysis of blueberry quality can be performed considering two assessment systems: hand-feel touch perception and mouthfeel (Table 1). Hand-feel touch evaluations are often conducted by gentle squeezing (or rolling) between the index and thumb fingers and scored from soft to firm (Sanford et al., 1991; Miller et al., 1993; Nunes et al., 2004; Rivera et al., 2013; Rodriguez and Zoffoli, 2016; Moggia et al., 2022). The commercial blueberry supply chain had mainly used hand-touch firmness to assess blueberry textural quality when instrumental devices were unavailable or when the texture was required to be evaluated by a low-cost and rapid methodology (Beaudry et al., 1998; Schotsmans et al., 2007; Cantin et al., 2012; Nunes, 2015; Rodriguez and Zoffoli, 2016; Moggia et al., 2022). However, tactile evaluation of berries can be inaccurate and inconsistent, and the assessor’s judgment can vastly influence the results (Slaughter and Rohrbach, 1985; Schotsmans et al., 2007). The use of assessors with enough training and

Table 1
Sensory attributes reported for blueberries.

Sensory system	Attribute	Description	Score	Reference
Hand-feel	Hand-touch firmness	Resistance force to berry deformation upon finger touch pressure	Soft to firm	Sanford et al. (1991);Miller et al. (1993); Beaudry et al. (1998);Nunes et al. (2004); Schotsmans et al. (2007);Nunes and Emond (2007);Rivera et al. (2013); Nunes, 2015; Rodriguez and Zoffoli, 2016;; Ktenioudaki et al. (2021); Moggia et al. (2022)
Mouthfeel	Firmness OR texture during chewing	Force required to break or fracture the blueberry sample between molars	Soft to firm	Ballinger et al. (1973); Rosenfeld et al. (1999);Saftner et al. (2008); Blaker et al. (2014);Lobos et al. (2014); Vilela et al. (2016)
	Crispness OR bursting energy	Force and sound as the berry breaks or fractures during the first or second chew	Mushy to crisp OR crunchy to rigid	Rosenfeld et al. (1999);Saftner et al. (2008); Blaker et al. (2014);Vilela et al. (2016)
	Juiciness OR succulence	Quantity of juice released from the flesh when chewed	Not juicy to juicy	Rosenfeld et al. (1999);Saftner et al. (2008); Blaker et al. (2014);Vilela et al. (2016)
	Graininess	Texture given by stone cells or seeds	Smooth to grainy	Blaker et al. (2014)
	Mealiness	Pasty or dry feeling in the mouth	Not mealy to mealy	Blaker et al. (2014)
	Skin toughness	Amount of residual skin during chewing after the flesh is gone	Tender to tough skin	Silva et al. (2005);Saftner et al. (2008); Blaker et al. (2014)
	Texture liking	Overall texture liking	-100 (greatest disliking) to 100 (greatest liking)	Gilbert et al. (2015)

experience is recommended to decrease variability when conducting hand-feel evaluations. However, growers and exporters have an ongoing interest in having an objective (instrumental) method to determine fresh blueberry firmness (Moggia et al., 2022).

Sensory evaluation conducted by mouthfeel or chewing is often performed by objective sensory techniques and sensory panels with a large population (e.g., >30) of previously trained or untrained consumers (Donahue et al., 2000; Saftner et al., 2008; Lobos et al., 2014; Gilbert et al., 2015) or experienced trained panellists (Blaker et al., 2014) with lower numbers of panellists. The evaluated attributes of the oral mastication test are obtained by scoring the sensations experienced at different stages of the mastication process (Table 1).

2.2. *Instrumental mechanical methods*

Among mechanical methods used for previous research on blueberry quality, the compression test is the most reported method to measure mechanical parameters (Table 2). Other mechanical tests have also been conducted, including penetration (puncture), impact, and shear tests (Table 2). In addition, during the last years, a double compression test, knowns as texture profile analysis, has been used in blueberry research due to its ability to imitate sensory descriptors (Chiabrando et al., 2009; Xie et al., 2018; Li et al., 2021; Olmedo et al., 2021; Rivera et al., 2021a; b; Giongo et al., 2022; Rivera et al., 2022). Several studies have considered a combination of different mechanical tests to assess blueberry quality (Silva et al., 2005; Blaker et al., 2014; Vance et al., 2017; Rivera et al., 2021a, 2022; Giongo et al., 2022).

Mechanical tests conducted on blueberries show a viscoelastic behaviour under mechanical loading, and hence mechanical properties of blueberries are mainly evaluated as a function of force, deformation, and time (Abbott, 1999). Consequently, when reporting the method, operational settings such as crosshead test-speed and maximum loading to a specific berry deformation (or penetration distance) must be clearly defined.

2.2.1. *Compression test*

Uniaxial compression tests often use the induction of a predefined deformation (i.e., change in length) of a blueberry sample by applying a loading perpendicular to the sample equatorial plane (i.e., normal stress direction) using a non-deformable probe of known dimension, which is moving at a constant crosshead speed.

The data is recorded in a force (y-axis) and deformation (x-axis) graph (Fig. 1**A,D**). The force-deformation curve often initiates when the compression probe contacts the blueberry and exceeds a minimum trigger force (e.g., 0.05 N). This trigger force is predefined by the operator and regulated by the equipment accuracy (Abbott, 1999; ASAE, 2008). During the test, force is recorded as the berry is deformed by the probe descending (downstroke) until reaching a target deformation distance (mm) or strain (% of deformation as a proportion of the initial fruit height), which is predetermined by the operator or the testing machine.

When performing a compression test (single or double compression), blueberries are often oriented with the stem-calyx axis perpendicular to the compression probe, and hence the deformation is conducted equatorially (Ballinger et al., 1973; Rohrbach and Mainland, 1993; Donahue and Work, 1998; Ferraz et al., 2001; Ehlenfeldt and Martin, 2002; Saftner et al., 2008; Ochmian, 2012; Leiva-Valenzuela et al., 2013; Blaker et al., 2014; Paniagua et al., 2014; Rivera et al., 2021a). Conversely, compression has also been performed by applying a load to the base of the berry (stem end to blossom end) (Ferraz et al., 2001; Ochmian, 2012). However, Ferraz et al. (2001) demonstrated that equatorial compression produces smoother and more consistent force-deformation curves than compression from stem-end to blossom-end of the berry.

Alternatively, a compression test has also been conducted by recording the maximum force to 30 mm compression of a group of

Table 2
Mechanical parameters for each instrumental test, previously evaluated on blueberries.

Instrumental test	Mechanical parameter	Unit	Indicator	Reference
Compression test (Fig. 1A,C, D)	Maximum force	N	Maximum force by using a target compression distance or deformation strain	Ferraz et al. (2001); Schotsmans et al. (2007);Paniagua et al. (2013);Vilela et al. (2016); Scheidt and Silva (2018);Moggia et al. (2022)
	Rupture point	N	Maximum force to berry rupture (berry releasing juice)	Silva et al. (2005)
	Chord stiffness, loading slope OR FirmTech firmness	N mm^{-1}	Rate of force increment by deformation distance. Calculated as the slope of the chord drawn between any specific points on the force-deformation curve	Timm et al. (1996); Slaughter and Rohrbach (1985); Rohrbach and Mainland (1993); Ehlenfeldt and Martin (2002); NeSmith et al. (2005);Saftner et al. (2008);Li et al. (2011); Leiva-Valenzuela et al. (2013);Blaker et al. (2014); Moggia et al. (2017);Vance et al. (2017);Cappai et al. (2018);Rivera et al. (2021a); Moggia et al. (2022);Rivera et al. (2022)
	Apparent modulus of elasticity	MPa	Deformation behaviour of a viscoelastic material	Prussia et al. (2006);Donahue and Work (1998); Rivera et al. (2021a);Giongo et al. (2022)
Penetration (puncture) test (Fig. 1 B)	Skin break force OR skin toughness	N	Penetration force required to pierce the skin	Forney et al. (2003);Silva et al. (2005);Duarte et al. (2009);Giongo et al. (2013); Concha-Meyer et al. (2015);Vance et al. (2017); Jaramillo-Sánchez et al. (2019); Jaramillo-Sánchez et al. (2021);Hu et al. (2021);Rivera et al. (2021a), Giongo et al. (2022);Rivera et al. (2022)
	Distance at the skin rupture point	mm or strain %	Probe displacement at epidermis rupture	Giongo et al. (2013); Jaramillo-Sánchez et al. (2019); Jaramillo-Sánchez et al. (2021);Rivera et al. (2021a); Giongo et al. (2022);Rivera et al. (2022)
	Skin break work energy	J	Work energy that is needed to break the epidermal skin	Jaramillo-Sánchez et al. (2019); Jaramillo-Sánchez et al. (2021);Rivera et al. (2021a);

(*continued on next page*)

Table 2 (*continued*)

Instrumental test	Mechanical parameter	Unit	Indicator	Reference
				Giongo et al. (2022);Rivera et al. (2022)
	Stiffness	N mm^{-1} OR N $\%^{-1}$	The slope of the initial linear portion of the force-deformation curve	Giongo et al. (2013); Jaramillo-Sánchez et al. (2019); Jaramillo-Sánchez et al. (2021); Giongo et al. (2022);Rivera et al. (2022)
Texture Profile Analysis (Fig. 1 C)	Hardness		Maximum force during the first compression cycle	Chiabrando et al. (2009);Xie et al. (2018);Li et al. (2021);Olmedo et al. (2021);Rivera et al. (2021a); Giongo et al. (2022);Rivera et al. (2022)
	Resilience	Ratio (-)	Success in regaining the original berry height during withdrawal of the first compression. Calculated as A1w/A1 in Fig. 1 C	Chiabrando et al. (2009);Xie et al. (2018);Rivera et al. (2021a);Giongo et al. (2022);Rivera et al. (2022)
	Cohesiveness	Ratio (-)	Strength of the internal bond comprising the berry body. Calculated as (A2 +A2w)/(A1 +A1w) in Fig. 1 C	Chiabrando et al. (2009);Xie et al. (2018);Li et al. (2021);Rivera et al. (2021a);Giongo et al. (2022);Rivera et al. (2022)
	Gumminess	N	Force necessary to chew a semisolid until ready for swallowing. Calculated as the multiplication of hardness and cohesiveness	Chiabrando et al. (2009);Giongo et al. (2022)
	Chewiness	J	Energy needed to chew a solid food until ready for swallowing. Calculated as the multiplication of hardness, cohesiveness, and d2 (Fig. 1 C)	Chiabrando et al. (2009);Li et al. (2021);Giongo et al. (2022).
	Springiness 1	Ratio (-)	How well the berry springs back after the first compression force is removed. Calculated as d2/d1 from Fig. 1 C	Xie et al. (2018); Rivera et al. (2021a);Li et al. (2021);Giongo et al. (2022);Rivera et al. (2022)
	Springiness 2	mm	Distance recovered by the sample between the end of the first bite and the start of the second bite. Calculated as d2 from Fig. 1 C	Chiabrando et al. (2009);Giongo et al. (2022)
Impact force response (drop test)	Contact time	s	Duration of the impact when the berry is dropped from a fixed height	Patel et al. (1993)
Shear test	Shear force	N g^{-1}	Maximum force peak, often related to the skin break	Makus and Morris (1993);Silva et al. (2005)
	Shear energy	J	Indicator of the internal strength of bonds of the berry	Silva et al. (2005)
Laser air-puff	Laser air-puff firmness index	kPa mm^{-1}	Air tank pressure divided by the maximum deformation displacement	Li et al. (2011)
	Springiness index	Ratio (-)	Indicator of the elasticity of the berry.	

blueberries (i.e., 30 g) placed in a plastic beaker or cylinder of defined diameter (Sanford et al., 1991; Nunes, 2015; Ktenioudaki et al., 2021). This kind of compression test, where a group of berries are compressed in bulk (and consequently mass data is collected), represents a viable option when data collection speed is prioritised. However, this technique is also likely to introduce considerable inconsistencies, such as variations in the contact area between berries interacting during the test. Hence, it is unclear whether this simultaneous compression of a group of berries generates data that accurately tracks blueberry quality and consumer acceptability.

The results from a compression test are often an approximately linear increase of force as the berry is deformed to ~25 % strain of its equatorial diameter (Ballinger et al., 1973; Rohrbach and Mainland, 1993). However, when the compression test is used for blueberries with high water loss (e.g., > 7 %), the loading portion of the force-deformation plot, measured with a crosshead speed of 1 mm s^{-1}, may follow a less linear (curved upward) pattern compared to berries with water loss lower than 1 % (Rivera et al., 2022). The curved portion of the force-deformation plot of blueberries with high water loss may indicate less elastic deformation as low turgor pressure may be expected on those blueberries.

When berries are compressed beyond 25 % of their initial diameter, the increase in force (as the probe compresses the berry) can be halted when the berry rupture point is achieved, which is abruptly followed by a continuous decrease of force (Fig. 1A). The rupture point in the force-deformation curve can also be accompanied by a visible failure of the berry structure (ASAE, 2008). For example, Silva et al. (2005) evaluated maximum compression force as the point the blueberry began releasing juice.

Blueberry compression is usually performed to a small target deformation (e.g., ≤ 2 mm), which does not produce a visible rupture point, and consequently, the test has been referred to as non-destructive compression (Timm et al., 1996; Ferraz et al., 2001; Chiabrando and Giacalone, 2011; Falagan et al., 2020). An advantage of non-destructive

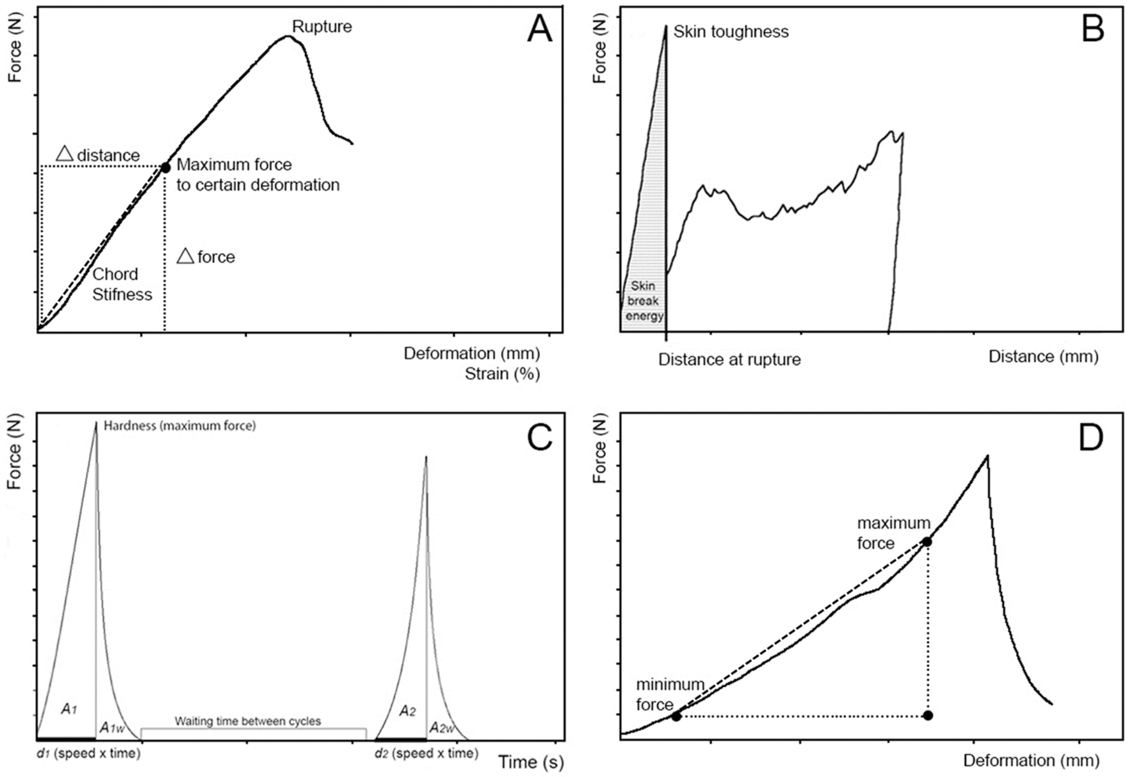

Fig. 1. Graphical representation of mechanical tests performed using a texture analyzer (A-C) and FirmTech compression device (D). A. Single compression test to 50 % deformation of the equatorial diameter of 'Rahi' blueberry, using a compression plate of 25 mm diameter. In this example, the rupture point occurred at approximately 35 % strain (5 mm deformation). B. Penetration test performed using a 2 mm needle probe to 25 % deformation of blueberry 'Rahi'. In this example, the needle probe breaks the skin at approximately 4.0 % strain (0.6 mm deformation). C. Texture profile analysis to 15 % deformation on blueberry 'Rahi'. See Table 1 to further calculation procedures of the mechanical parameters obtained from the double compression graph. D. Compression test recorded by a FirmTech 2 device using a compression plate. FirmTech firmness is calculated as the slope of the force-deformation between the minimum and maximum force thresholds (adapted from Donahue et al., 2000).

methodologies is that it allows tracking quality changes of the same fruit throughout postharvest storage. However, the compression test can only be considered a valid non-destructive methodology when fruit cellular structure is unaffected. Even a gentle plate compression to 1.5 N (e.g., 1–2 mm deformation) can induce micro-cracks in the blueberry microscopic structure (Allan-Wojtas et al., 2001). Consequnetly, multiple rounds of berry compression might affect the results, most likely actively reducing the firmness of the fruit. Further research is required to test whether multiple compressions (temporally dispersed) at small compression forces (e.g., $<$ 0.5 N) can skew data in the resulting datasets.

2.2.2. Probes used for compression test

Different probe types have been used to conduct compression tests and can be divided into flat surface plates of high contact area (e.g., $>$ 15 mm dimeter plate) or cylindrical probes of contact area smaller than the blueberry diameter (e.g., 2–4 mm area).

Flat surface plates are standard compression probes that can be used to conduct parallel plate contact compression (ASAE, 2008). A common requirement is that the plate should be larger than the fruit surface contact area, facilitating the evaluation of compression mechanics of the whole fruit (Harker et al., 1997). Reported dimensions of the compression plates used on blueberries often vary between 15 mm and 75 mm in diameter (Prussia et al., 2006; Schotsmans et al., 2007; Rivera et al., 2013, 2021a; Paniagua et al., 2013; Cantin et al., 2012; Vilela et al., 2016; Moggia et al., 2017; Lobos et al., 2018; Falagan et al., 2020; Giongo et al., 2022). A compression plate is also the main probe used when mechanical parameters are analysed by a FirmTech compression machine (Prussia et al., 2006). However, plates have also been used in the texture analyser equipments (Schotsmans et al., 2007; Paniagua et al., 2013; Cantin et al., 2012; Rivera et al., 2013; Vilela et al., 2016; Hu et al., 2015); Instron universal testing machine (Donahue and Work, 1998; Ferraz et al., 2001); and Ametek force gauge (Rohrbach and Mainland, 1993).

Cylindrical probes are often of small diameter (2–4 mm) with a flat or domed tip (Blaker et al., 2014; Chiabrando and Giacalone, 2011; Concha-Meyer et al., 2015; Rodriguez and Zoffoli, 2016; Scheidt and Silva, 2018; Ortiz et al., 2018; Manzi and Lado, 2019; Moggia et al., 2022). Small cylindrical probes have been used on various testing machines, including texture analyser (Vicente et al., 2007; Angeletti et al., 2010; Ortiz et al, 2018; Manzi and Lado, 2019), Instron universal testing machines (Blaker et al., 2014); and durometers (Chiabrando and Giacalone, 2011; Rodriguez and Zoffoli, 2016; Moggia et al., 2022).

Compression test performed using a small cylindrical probe ($<$ 4 mm) can potentially puncture the blueberry skin, penetrating all the way to the flesh tissue. Under this condition, the method should be considered as a penetration (or puncture) test rather than compression. Consequently, research studies should explicitly declare if the skin is punctured or not when a small cylindrical probe is used. An example of this would be the penetration method reported by Giongo et al., (2013, 2022) or the compression test reported by Moggia et al. (2022).

Small cylindrical probes generate significantly different results from assays that employ compression plates. Small probes provide a smaller contact area than plate probes; hence, smaller forces are achieved compared with a compression plate executed to the same target deformation distance (e.g., 1 or 2 mm). In addition, for compression using a plate probe, the area of contact with a spherical fruit surface (i.e., blueberry), may increase as deformation distance increases. While, when using small cylindrical probes, the area of contact with fruit surface may not be influenced by the deformation distance (Moggia et al., 2022). Consequently, these differences can influence subsequent quantification of mechanical parameters and hence interpretation of the result.

2.2.3. *Mechanical parameters from the compression test*

Mathematical processing of the compression test data described in force-deformation graph enables simultaneous calculation of different mechanical parameters and subsequent adimensional indexes. The most frequently reported parameters from compression tests conducted on blueberry are the maximum force (N) and slope of force-deformation downstroke compression plot, also knowns as chord stiffness (kN m^{-1}) (Table 2; Fig. 1A). Other mechanical parameters, such as apparent modulus of elasticity (Pa), have also been reported (Table 2).

The maximum force (N) is often calculated as the force achieved at a predefined deformation distance (mm) or strain (%) of equatorial berry diameter (Fig. 1A). However, if the deformation distance exceeds maximum resistance of berry cellular structure, maximum force may be measured at the deformation distance equivalent to the rupture point (N) (ASAE, 2008; Fig. 1A).

Chord stiffness, loading slope, and FirmTech firmness (kN m^{-1}) refer to the same mechanical parameter, being the rate of force increase as the blueberry is deformed. Chord stiffness is calculated as the straight-line slope drawn between two specific points on the force-deformation curve (Eq. 1, Slaughter and Rohrbach, 1985, Fig 1D).

$$CS = \frac{F_m - F_0}{\mathrm{D}} \tag{1}$$

Where Fm and F_0 are the maximum and minimum force (N), respectively, and D is the deformation (mm) of a blueberry which is achieved between the minimum and maximum force.

The most common procedure considers the use of a minimum force equal to the trigger force and the maximum force achieved at a predefined small deformation (< 25 % strain) (Ballinger et al., 1973; Slaughter and Rohrbach, 1985; Rivera et al., 2021a, 2022). Alternatively, when using the FirmTech compression device, firmness is calculated as the loading slope between a minimum and maximum force thresholds predefined by the operator (Fig. 1D). However, it is important to keep in mind that the threshold minimum and maximum force selected for the calculation of the loading slope can influence the output result (Prussia et al., 2006). Hence it is recommended that operational settings are reported in research publications, and over the course of time, and standard predetermined settings are used across research studies and instruments to enable data standardization. As an example, studies conducted by Moggia et al. (2016, 2017), Arrington and DeVetter, (2017), and Lobos et al. (2018, 2021) all have used FirmTech operation settings previously reported by Ehlenfeldt and Martin (2002) of 0.15 N and 1.96 N as minimum and maximum force thresholds. Consequently, it is recommended to use the same operational settings as other previous studies when chord stiffness data is required to be comparable.

The apparent modulus of elasticity (Pa) is a direct descriptor of the elastic properties or the deformation behaviour of fruit commodities (Prussia et al., 2006; ASAE, 2008; Giongo et al., 2013). Modulus of elasticity is routinely determined as the ratio of stress (force per cross-sectional area of the probe) to strain (% or mm) and should only be measured considering the non-destructive elastic portion of the force-deformation curve (Abbott, 1999).

Assuming that the fruit is viscoelastic and the compression deformations are small (<25% berry diameter), for fruit materials of convex shape (i.e., blueberry) compressed using parallel plate contact, the apparent modulus of elasticity can be determined using Eq. 2, which is based on Hertz contact theory (Donahue and Work, 1998; Prussia et al., 2006; ASAE, 2008).

$$E = \frac{0.338\ F\ (1-\mu^2)}{D^{3/2}} \times \left[\mathrm{K_U} \times \left(\frac{1}{\mathrm{R_U}} + \frac{1}{\mathrm{R'_U}}\right)^{1/3} + \mathrm{K_L} \times \left(\frac{1}{\mathrm{R_L}} + \frac{1}{\mathrm{R'_L}}\right)^{1/3}\right]^{3/2} \tag{2}$$

Where E is the apparent modulus of elasticity (Pa); F is the force (N) measured by the load cell on the testing machine; D is the blueberry deformation (m) at the given force; $\mathrm{R_U}$ and $\mathrm{R'_U}$ are the minimum and maximum, respectively, radii of curvature (m) at the upper point of contact (plate probe); $\mathrm{R_L}$ and $\mathrm{R'_L}$ are the minimum and maximum, respectively, radii of curvature (m) at the lower point of contact (platform support). $\mathrm{K_U}$ and $\mathrm{K_L}$ are constants calculated as 1.351 for contact angle to plate probe of 90° (ASAE, 2008). μ is the Poisson's ratio (dimensionless), which measures the deformation of the food material in the perpendicular direction to the uniaxial compression. Poisson ratio is assumed for blueberries to be a value close to 0.4 (Prussia et al., 2006). Alternatively, Poisson's ratio can be further calculated considering calculation procedures described by Lu and Abbott, (2004) or Sirisomboon et al. (2012).

2.2.4. *Penetration test*

A penetration (puncture) test is a destructive method that combines stresses achieved by force of compression (normal direction) and shear (tangential direction) as recorded by the downstroke movement and penetration of a non-deformable probe of predefined shape and dimension into a target depth at the fruit equator (Harker et al., 1997; Lu and Abbott, 2004). For most of the firm fleshed fruits such as apple, kiwifruit, and peach, a penetration test is a standard firmness method universally used for quality evaluations (Harker et al., 1997; Abbott, 1999). In this case, the test involves penetration of a cylindrical probe into the flesh of a peeled fruit (Harker et al., 1997; Abbott, 1999). However, on soft fleshed fruits, the penetration test is commonly conducted on fruits with intact peel, and hence the probe must break the skin before penetrating the flesh tissue. This procedure has been reported for grapes (Letaief et al., 2008), raspberries (Giongo et al., 2019), and blueberries (Forney et al., 2003; Duarte et al., 2009; Giongo et al., 2013, 2022; Concha-Meyer et al., 2015; Vance et al., 2017; Rivera et al., 2021a).

As in the case of the compression test, the assessor should perform a penetration test using predefined operational settings of trigger force, test speed, and target penetration distance. The resulting data is recorded in a force (y-axis) and distance (x-axis) graph (Fig. 1B).

2.2.4.1. Probes used on penetration test. Probes previously used to collect penetration parameters of blueberries include needle probes such as the P/2 N (Stable Micros Systems, UK) of 2 mm maximum diameter and 0.39 mm tip diameter (Rivera et al., 2021a; b); or the 1.8 mm maximum diameter (item 320398, ZwickRoell, Italy) reported by Giongo et al. (2022). Other probes for penetration test include cylindrical flat end probes of 2 mm (Silva et al., 2005; Concha-Meyer et al., 2015; Giongo et al., 2022), 3 mm (Jaramillo-Sánchez et al., 2019; Jaramillo-Sánchez et al., 2021), or 4 mm diameter (Giongo et al., 2013, 2022).

When using needle probes, test machines with high accuracy at relatively low force and resolution are required to measure mechanical parameters because the skin breakpoint is usually achieved below the 1 N of force. This includes testing devices such as texture analysers equipped with a 5 kg load cell (Rivera et al., 2021a; Giongo et al., 2022) and less sophisticated Wagner force gauges (Forney et al., 2003; Vance et al., 2017).

2.2.4.2. Mechanical parameters for the penetration test. Previously reported mechanical parameters for a penetration test are often related to the moment when blueberry skin breaks (or is pierced). For example, force at skin break or skin toughness (N), skin break distance (mm or %), and skin break energy (J) have been reported (Table 2).

Skin break force is the most reported mechanical parameter on blueberries when using penetration test (Table 2). This parameter is detected on the standard force-distance curve, as the force achieved just before an abrupt and constant decrease in force coincides with the point of visible penetration of the skin by a non-deformable probe (Fig. 1B).

Although skin break force is measured at the point of skin break, the structural support and elasticity offered by the flesh of the fruit may also contribute to the final measurement. Hence what is usually referred to as "skin break force" might measure the additive resistances of flesh and skin tissues. Silva et al. (2005) reported that an average of 45% less force was required across five different blueberry genotypes when the skin was pierced from inside to outside the blueberry compared to the force achieved by rupturing the skin from outside to inside the berry.

Other essential parameters obtained from the puncture penetration test included: the distance at skin break and skin break work energy (Table 2). In addition, the penetration test conducted using a needle probe can provide additional mechanical parameters related to the characterisation of different tissue layers of blueberry, such as epidermis, hypodermis, and parenchyma (Giongo et al., 2022).

2.2.5. *Texture profile analysis*

A particular example of a mechanical test that attempts to estimate food's sensory descriptors instrumentally is the texture profile analysis (TPA). This test aims to imitate the oral chewing by performing two consecutive compressions of the food sample using a flat rigid plate (Pons and Fiszman, 1996). Data is obtained from the force (y-axis) and time (x-axis) curves (Fig. 1C). To accurately measure the mechanical parameters of the force-time graph, a constant crosshead speed must be set for the downstroke and the upstroke of both cycles. Additional settings predefined by the operator include the compression target strain (% of deformation related to initial fruit length) and the waiting time between compression cycles influence the results. TPA has been used on diverse fruit produce, including pomes (Guine, 2013), drupes (Contador et al., 2016), and small berries such as grapes (Letaief et al., 2008), raspberries (Giongo et al., 2019), and blueberries (Table 2).

Adaptations or optimisations have been proposed to the original TPA test through the short history of its use on blueberries.

1. Hardness, chewiness, springiness, resilience, cohesiveness, and gumminess are the most common TPA descriptors utilised for blueberries (Table 2). However, to be very strict with the original TPA definitions, the descriptor of gumminess should not be reported for blueberries because it is only defined for semisolid foods (Pons and Fiszman, 1996).
2. Standard size samples are recommended when using TPA (Pons and Fiszman, 1996). However, preparing even-size samples using cork borers and knives as done in other fruit such as peach (Contador et al., 2016) and melon (Lazaro and de Lorenzo, 2015) is impractical for blueberry due to the small fruit size and relatively soft flesh texture. Consequently, the test has previously been performed using a whole intact berry (Chiabrando et al., 2009; Xie et al., 2018; Li et al., 2021; Olmedo et al., 2021; Rivera et al., 2021a, 2022; Giongo et al., 2022). One of the main challenges of using the whole berry is the variability in sample dimensions which influences the force quantification. Fruit with the same material properties can produce different hardness (at a predefined deformation strain %) if the sample size varies greatly (Trinh and Glasgow, 2012). Hence, when conducting TPA, the selection of blueberries in the same range of equatorial diameter is recommended. In addition, the chord stiffness (Rohrbach and Mainland, 1993) and modulus of elasticity (Trinh and Glasgow, 2012) have been preferred to hardness.
3. Input operational settings of compression speed, strain distance, and time duration between compression cycles can influence TPA parameters such as hardness, cohesiveness, springiness, and chewiness (Alvarez et al., 2002; Rosenthal, 2010; Madieta et al., 2011; Rivera et al., 2021b). For blueberries, TPA has been previously conducted by selecting any of two compression strain distances, 15% (Rivera et al., 2021a; b; Li et al., 2021) or 30% (Chiabrando et al., 2009; Xie et al., 2018; Rivera et al., 2021b; Giongo et al., 2022). However, Rivera et al. (2021b) showed that TPA performed to 15 % strain deformation (approximately 2 mm) better differentiated mechanical differences on 'Nui' and 'Rahi' blueberries with different water loss levels.

2.2.6. *Other mechanical tests*

Other tests used to characterise mechanical parameters but not extensively used by the research community when evaluating blueberry quality are the impact response analysis (drop test), the shear test and laser air-puff.

The impact response analysis considers that differences in fruit bounce can be used to measure firmness (Patel et al., 1993; McGlone and Schaare, 1998). A soft blueberry of equal mass will have a more prolonged contact duration (s) than a firm berry when bouncing after it is dropped from a predetermined height (Patel et al., 1993). The impact response has provided the basis for commercial grading systems, such as the SoftSort grader described for kiwifruit (McGlone and Schaare, 1998).

The shear test determines the shear force and energy when cutting a solid food sample into pieces using a sharp knife (Lu and Abbott, 2004; Silva et al., 2005). Although this test is more recommended on muscle foods (i.e., meats) rather than fruit (Lu and Abbott, 2004), the test has previously been conducted on blueberries (Makus and Morris, 1993; Silva et al., 2005). Two mechanical parameters, shear force and maximum energy, have been previously reported on different cultivars (Table 2). For calculating the shear force, Makus and Morris (1993) performed the shearing test on a group of 150 g of fruit using a TP-1A texture press (Food Technology Corp., USA). Silva et al. (2005) executed the test on a group of 50 berries using a Kramer shear press (Food Texture Corp, USA). In this last study, the sheer force provided similar cultivar differentiation compared to the maximum force by a penetration test (Silva et al., 2005).

A very innovative test to evaluate firmness as a non-contact mechanical method is the laser air-puff method developed by the University of Georgia, USA (Li et al., 2011). The method is based on blueberry deformation, generated by a brief puff of pressurised air and measured using a laser displacement sensor. The test is based on the concept that a softer fruit would have higher deformation. This method can obtain two parameters on blueberries, the laser air-puff firmness index and the springiness index (Table 2).

2.3. *Mechanical testing machines*

Texture analysers (e.g., Stable Micro System, UK or Zwick Roell, Italy), FirmTech 2 (Bioworks, USA), Universal Testing Machine (Instron, USA), force gauges (e.g., Ametek, USA; Wagner, USA) and durometers (e.g., Durofel®, France) are the most common testing machines used to assess mechanical properties of blueberry (Rivera et al., 2021a). The Stable texture analyser, Instron universal testing machines, and FirmTech 2 compression devices used in blueberry research often follow the procedures recommended by the ASABE Standards of "*compression test of food materials of convex shape*" (ASAE, 2008). The most important recommendations can be summarised as follows:

1. Suitable testing machine equipment records the change in deformation as a function of the load applied to the berry.
2. The load should be recorded with an accuracy of ± 1% of the maximum expected value.
3. The equipment should allow setting a constant compression rate (crosshead speed).
4. A hardened metal plate with a smooth surface should be used to support the sample.

Adaptions to this last recommended formality (4) have also been reported, especially when using parallel plate compression. Due to the oblate spheroid shape and the small contact area for blueberry, balancing and restricting the movement of the berry prior to and during compression is important to ensure accurate mechanical measurements. To avoid the balancing movement, berries can be held over a small flat metal washer ring of 7–10 mm internal diameter using an Instron universal testing machine (Ballinger et al., 1973) or Stable texture analyser (Paniagua et al., 2013; Rivera et al., 2021a, 2022). For the FirmTech compression device, the design considers an adaptation of the platform support where berries are held during compression. A turntable with 25 shallow depressions of 10 mm diameter and 2 mm depth enables support for each of 25 berries during the automated compression procedure (Prussia et al., 2006; Mitcham et al., 1998).

Although the different testing machines can be used to calculate the same mechanical parameter (e.g., FirmTech firmness compared to Instron chord stiffness), the equipment varies in precision, resolution, operation ease, and cost. In addition, FirmTech, texture analysers, and Instron Universal Testing Machine can perform fully automatic tests, while analog and electronic durometers and force gauges often require human interaction with the fruit sample during the assessment.

The recommendation of when to use each instrumental device will depend on the objective of the data collection and the portability of the device. Stable texture analyser or Instron universal testing machine is recommended when data must be obtained with a high precision, resolution, and accuracy of operational settings (e.g., constant loading rate). These conditions allow assumptions that most of the data variation is attributed to natural berry to berry variation rather than an instrumental error (Slaughter and Rohrbach, 1985). In addition, when using texture analyzers or Instron universal testing machines, a vast range of mechanical tests can be conducted and parameters extracted, which is facilitated by the relative ease of procedures related to changing the operational settings (e.g., number of compression cycles, crosshead speeds, and target modes) and hardware components (e.g., probe type, load cell capacity).

On the other hand, when mechanical tests are used to evaluate mechanical parameters under commercial quality control operations, where mass data collection may be required, trade-offs between accuracy, speed of data collection, portability, and cost may be necessary. Texture analysers and Instron universal testing machine might not be ideal due to the slow operational speed (limiting the sample size), lack of portability, and the high investment and operational cost. Considering the instrumental options available in the market and previously reported for blueberry studies, the Wagner force gauge (Forney et al., 2003; Vance et al., 2017), Durofel durometer (Chiabrando et al., 2009; Rodriguez and Zoffoli, 2016), Penefel durometer (Moggia et al., 2022), and Ametek force gauge (Sanford et al., 1991; Patel et al., 1993; Rohrbach and Mainland, 1993) are portable instruments that provide lower cost, higher speed, and higher throughput solutions to collect information. The FirmTech compression device seems to offer a compromise between all the parameters mentioned above and can be used in commercial evaluations (Prussia et al., 2006; Moggia et al., 2022). A positive feature of FirmTech compared to other testing machines is that it provides a fully automatic operation for each evaluation batch of up to 25 berries in its unique designed turntable, which can further reduce the labour cost of operations (Mitcham et al., 1998; Prussia et al., 2006). In addition, Moggia et al. (2022) demonstrated that different FirmTech 2 devices might provide comparable results when devices are properly calibrated and the same operational parameters are used. It is recommended to measure standard rubber balls, to check that FirmTech is performing accurate readings before its use (Prussia et al., 2006; NeSmith et al., 2005).

On the other hand, commercial orientated equipment can have significant limitations. The main limitations for durometer (i.e., Durofel) and force gauges are related to operating procedures. The compression procedures often required the assessor to hold the fruit sample with one hand and perform the compression movement with the other hand holding the probe device. Hence, data error can be induced by different operators and by inaccuracies of the same operator (Patel et al., 1993). Consequently, intense training and experience are prerequisites for the operators to regulate the consistency of handheld device operation to eliminate potential errors introduced from variation in the compression angle, sample deformation distance, speed of movement, and the force applied by the assessor's fingers when holding the berry (Mitcham et al., 1998). An alternative solution to the force gauges is to mount this equipment on a motorised or mechanical stand to facilitate the standardisation of operation procedures (Rohrbach and Mainland, 1993).

An additional limitation of force gauges and durometers is that both instruments only report a single mechanical parameter. The maximum force to a compression distance (e.g., hardness to 2 mm) is provided when using a Shore durometer (Alsmairat et al., 2011) or Ametek force gauge (Patel et al., 1993), and the force to penetrate the skin (skin toughness) is found when using a Wagner gauge (Forney et al., 2003; Vance et al., 2017). Alternatively, Rohrbach and Mainland (1993) estimated the blueberry stiffness using an Ametek force transducer, knowing the compression displacement.

For durometers, an additional limitation is associated with the data unit, which is reported as a non-standard unit of force. For example, Shore durometer units range from 0 to 100 (Alsmairat et al., 2011), and the Durofel Index ranges from 1 to 60 (Chiabrando et al., 2009; Rodriguez and Zoffoli, 2016). For the Durofel, a linear regression model ($r^2 = 0.97$) can be used to transform the Durofel Index into Newtons (N), as proposed by Rodriguez and Zoffoli (2016).

The main limitations of the FirmTech 2 compression device can be related to its portability (a computer is required) and the mechanical test capability. The FirmTech firmness (g mm^{-1}) is the only mechanical property automatically calculated from the force-deformation curve (Donahue et al., 2000; Prussia et al., 2006; Moggia et al., 2017).

2.4. *Non-destructive techniques*

Automatic real-time inspection and grading of blueberry quality to facilitate sorting undesired soft berries is an important and growing interest for the commercial blueberry supply chain. The selection of a true non-destructive (non-invasive) technique may facilitate this commercial requirement. In addition, blueberries can experience firming or softening throughout storage as influenced by postharvest storage management of humidity (Paniagua et al., 2013; Rivera et al., 2021a), and atmosphere composition in controlled atmosphere (Rivera et al., 2022). Consequently, a non-invasive firmness method would benefit the research community to study mechanical changes of the same berry as influenced by postharvest management.

Non-invasive methods previously used in blueberries include electronic detectors of aromatic volatiles (Simon et al., 1996), and optical techniques such as hyperspectral microscope imaging (Park et al., 2022), optical coherence tomography (Li et al., 2021), and near-infrared (NIR) hyperspectral evaluation (Leiva-Valenzuela et al., 2013, 2014; Hu et al., 2016). These techniques usually do not measure firmness directly, and consequently, output data is first required to be related to mechanical parameters to provide a measure of firmness (Table 3).

Hyperspectral techniques have been the most studied non-destructive methods to assess blueberry mechanical parameters, producing acceptable prediction performance ($r = 0.6–0.9$) across studies (Table 3). Hyperspectral imaging of blueberries has previously been conducted with three different sensing configurations, including reflectance (Leiva-Valenzuela et al. (2013); Leiva-Valenzuela et al., 2014, transmittance (Leiva-Valenzuela et al., 2014), or interactance (Hu et al., 2016). However, Leiva-Valenzuela et al. (2014) indicated that reflectance sensing mode results in a better prediction of blueberry chord stiffness than transmittance and may be easier to implement in commercial operations. On the other hand, Hu et al. (2016) have demonstrated that hyperspectral imaging in interactance mode can be

Table 3
Use of non-invasive techniques to predict instrumental mechanical methods previously reported for blueberry.

Texture variation method	Non-destructive method		Mechanical method		Prediction performance (R)[a]	Reference
	Technique	Parameter	Machine, test	Parameter		
'Bluecrop' blueberry harvested at five maturities	Electronic sniffer	Aromatic volatiles	Force gauge, plate compression	Force at rupture point	0.62	Simon et al. (1996)
Commercial highbush blueberry stored for 3–14 d at 4 °C	Hyperspectral imaging	Reflectance sensing between 500 and 1000 nm	Texture Analyser, plate compression	Chord stiffness	0.83–0.87	Leiva-Valenzuela et al. (2013)
Commercial Rabbiteye blueberry stored for 3–14 d at 4 °C	Hyperspectral imaging	Reflectance sensing between 400 and 1000 nm	Texture analyser, plate compression	Chord stiffness	0.77	Leiva-Valenzuela et al. (2014)
		Transmittance sensing between 563 and 939 nm			0.59	
Two batches of commercial imported blueberry from Latin America and stored for 6 d at 4 °C	Hyperspectral imaging	Interactance sensing between 675 and 1000 nm	Texture analyser, texture profile analysis	Hardness, Springiness, Cohesiveness, Resilience	0.77 0.84 0.91 0.86	Hu et al. (2016)
			Texture analyser, penetration test	Skin toughness, Distance at skin break, Chord stiffness, Final force	0.71 0.65 0.58 0.62	
'Centurion' blueberry stored on four RHs at 4 °C	Optical coherence tomography	Cell thickness of first visible layer	Texture analyser, texture profile analysis	Hardness slope Cohesiveness, Springiness	-0.72 -0.80 0.88	Li et al. (2021)
Blueberry from two regions stored for 1–5 d at 20 °C	Hyperspectral microscope imaging	Average Intensity at 530 nm of parenchyma cell-wall	Texture analyser, penetration test	Maximum force	0.93	Park et al. (2022)

[a] Correlation coefficient.

used to predict mechanical parameters of the TPA and penetration test (Table 3).

A limitation of the experimental design of previously conducted studies in hyperspectral imaging is the lack of a strong and consistent manipulation of pre- or postharvest factors (e.g., genotype differences, harvest maturity, storage humidity management) to generate berries with different mechanical properties (Table 3). Consequently, the studies may have considered a relatively small range of mechanical parameter distribution (Leiva-Valenzuela et al., 2014), and the previously reported performances do not assure that the firmness prediction can be reproduced when mechanical properties are influenced by any other pre- or postharvest factor (Rivera et al., 2022).

In addition, hyperspectral imaging can generate models subject to overfitting, i.e., the model developed might only be deployable on a limited number of very similar conditions (Hu et al., 2016). However, changes in blueberry mechanical parameters can be attributed to different causes (e.g., water loss, cell wall degradation, presence of stone cells) that can potentially affect the spectra profiling of blueberries, biasing the results. Hence, further study of hyperspectral imaging considering different causes of mechanical changes may be required. As an example, other studies on non-destructive techniques have considered a clear strategy to manipulate mechanical parameters. Simon et al. (1996) used an electronic sniffer to study 'Bluecrop' of different maturity, and Li et al. (2021) used optical coherence tomography to study 'Centurion' stored in different humidity environments that produced different water loss levels.

3. Factors affecting textural and mechanical parameters

Firmness can impact blueberry consumption by influencing consumer preferences (Blaker et al., 2014), potential postharvest storage life (Hancock et al., 2008, 2022), and the likelihood of bruising due to mechanical impact damage (Moggia et al., 2017). Therefore, studying the pre- and postharvest factors influencing blueberry firmness is critical to assist marketability and quality improvements of blueberries. This section reviews the most studied factors influencing changes in mechanical parameters, including genotype, berry maturity management, calcium applications, and postharvest technologies (i.e., time, temperature, humidity, and controlled atmospheres). To identify the most widespread mechanical methods used to evaluate the effect of these factors on blueberries, a total of 62 references were grouped by the mechanical test method (Fig. 2A) and type of equipment used (Fig. 2B).

3.1. Blueberry genotype

Blueberries belong to the *Ericaceae* family and *Vaccinium* genus. The most cultivated blueberry types worldwide are highbush blueberry (including *V. corymbosum* L. and interspecific hybrids of *Vaccinium* genus) and rabbiteye blueberry (*Vaccinium ashei* Reade; syn. *V. virgatum* Ait.). For each blueberry type, a long list of cultivars has been reported, and this list is expected to increase due to the ongoing expansion of blueberry breeding programs worldwide (Lobos et al., 2015; Cappai et al., 2018). Along with the increase in available cultivars, improvement in blueberry textural characteristics is expected. Considering data from 1915 to 2015, Cappai et al. (2018) described a positive linear relationship between FirmTech firmness and the time (year) that the cultivar was released.

Firmness is a genetically controlled trait (Cappai et al., 2018, 2020), and hence genotype of a given blueberry is a factor that will impact firmness. Differences in texture and mechanical parameters have previously been described for different genotypes. These differences are potentially associated with microstructural characteristics, including cell size, degree of cell-to-cell contact and air space, thickening of the parenchyma cell wall, and the number of stone cells (Allan-Wojtas, 2001). In addition, differences in mechanical properties of blueberry genotypes have also been related to the cell wall chemical composition (Silva et al., 2005). Conversely, Blaker and Olmstead (2015) found that the differences in quantitative cell wall material evaluations did not associate with textural differences when comparing standard texture genotypes with the genotypes displaying a crisp sensory texture (see *4.2.1 blueberry crispness* for further description of crisp texture).

Sensory and instrumental methods have been considered to characterise texture differences of blueberry genotypes. Sensory attributes obtained by oral evaluation (Table 1) have been commonly used to assess genotypic differences (Donahue et al., 2000; Saftner et al., 2008; Blaker et al., 2014; Vilela et al., 2016), and plate compression is the most

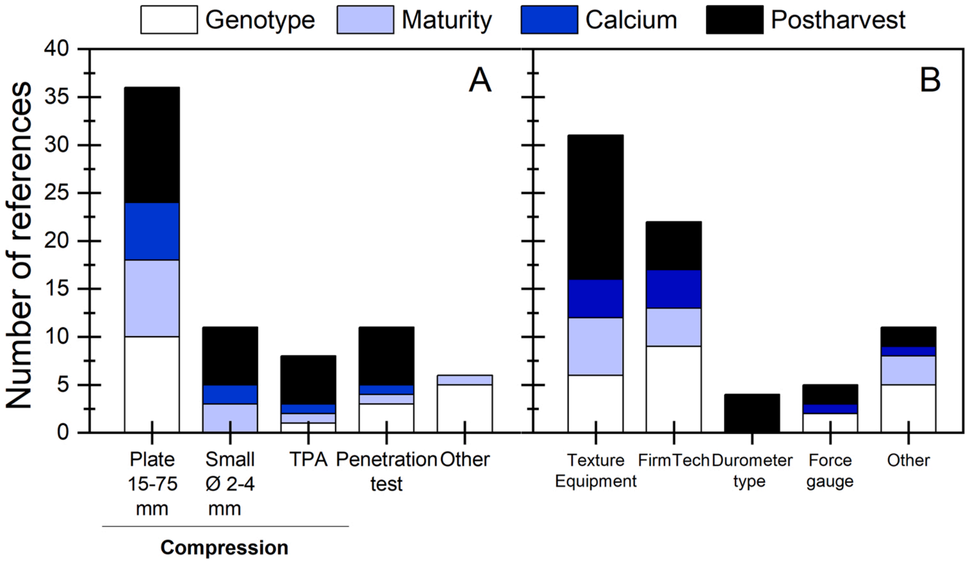

Fig. 2. Mechanical test methods (A) and equipment types (B) that have previously been used to evaluate the influence of pre- and postharvest factors on the mechanical parameters of blueberry. Other test methods (in A) include shear test, impact response analysis and laser-air puff. Texture equipment (in B) includes texture analysers and Instron universal testing machine. This figure was constructed using 62 previously reported studies. For details of each reference, see Supplementary Table 1.

used instrumental test (Fig. 2A). In addition, the FirmTech is the most common instrument used due to the rapid and automatic evaluation of multiple blueberry samples (Cappai et al., 2018).

When measuring the firmness of multiple genotypes, the reported coefficient of variation of average firmness data obtained by FirmTech was approximately 15% (Ehlenfeldt and Martin, 2002; NeSmith et al., 2005; Saftner et al., 2008; Blaker et al., 2014). Chord stiffness determined using Instron universal testing machine or a texture analyser also revealed similar levels of variation between cultivars (Rohrbach and Mainland, 1993; Giongo et al., 2022).

Other tests have also been used to detect genotypic differences. A penetration test has provided differences between highbush and rabbiteye blueberry types, with the cultivars of rabbiteye having higher skin toughness (Silva et al., 2005). Giongo et al. (2022) characterised mechanical differences between commercially available and advanced selection genotypes using a multi-parameter approach that included penetration tests with flat probes of 2 mm, 4 mm, and a needle probe along with texture profile analysis.

The use of alternative methods, such as the shear test (Silva et al., 2005; Makus and Morris, 1993), impact response analysis (Patel et al., 1993; Simon et al., 1996), and laser air-puff parameters (Li et al., 2001), have also identified differences between blueberry cultivars.

3.2. *Berry development and harvest maturity*

Blueberry maturity at harvest can affect the eating experience of consumers. Appearance (i.e., surface colour and size), flavour (i.e., ratio of total soluble solids to acidity), and softening (i.e., firmness) have been reported to change during the late maturity development of blueberries attached to the plant (Moggia et al., 2018). Consequently, blueberries are harvested when these characteristics maximise the eating experience, which is often related to 100 % surface blue colour berries or full maturity (Forney, 2009; Moggia et al., 2018).

Some developmental changes, such as external fruit colour, and berry size, can be easily measured. However, more sophisticated evaluation techniques are required to detect changes in flavour (increased total soluble solids and decreased acidity) and changes in texture (Giongo et al., 2013; Moggia et al., 2018). Blueberry flavour can be partly characterised using the universal instrumental methods of refractometry and titration to analyse the soluble solids and acidity, respectively (Moggia et al., 2018). However, when textural changes are evaluated, different techniques can be used. Biochemical analysis of cell wall modifications, including pectin and hemicellulose, can be performed to detect softening (Proctor and Miesle, 1991; Vicente et al., 2007; Chea et al., 2019). However, these methods are highly sophisticated and cannot be used on routine quality evaluations. Consequently, a mechanical test may be more appropriate.

The compression test has been the preferred method to evaluate mechanical parameters during blueberry growth and development (Fig. 2). Consequently, the parameters of maximum force to a predefined deformation (Vicente et al., 2007; Hancock et al., 2008; Chea et al., 2019; Lin et al., 2020), and chord stiffness (Ballinger et al., 1973; Timm et al., 1996) or FirmTech firmness (Moggia et al., 2016, 2018) have previously been used to assess maturity changes. On the other hand, Rivera et al. (2022) demonstrated that force at skin break (N) obtained by penetration test was the best mechanical parameter to differentiate between immature, mature, and overmature harvested berries.

Significant softening changes during fruit development were previously described. A higher softening rate was observed at the early ripening stages, specifically when the berry surface turned green to red (Ballinger et al., 1973; Vicente et al., 2007; Moggia et al., 2018; Chea et al., 2019). A second important softening has been described between surface colour change from 50 % pink to 100 % blue surface colour and continues to occur if berries are kept for a longer period on the plant and hence become overmature (Moggia et al., 2018; Rivera et al., 2022). Consequently, even an outstanding firmness genotype harvested at an overmature stage can present a significant prevalence of soft berries, affecting the average firmness of the harvested batch (Lobos et al., 2018; Moggia et al., 2018; Rivera et al., 2022).

Only one article reports an alternative method to evaluate blueberry maturity, which used the impact response analysis (Patel et al., 1993). The contact time increased as the maturity stage of 'Centurion' increased from green to overripe blue fruit, indicating that the advanced maturity berry may be softer.

3.3. *Calcium management*

Calcium plays an essential role in fruit ripening and quality, including regulating metabolism, physiological disorders, and maintaining cell structural integrity (Ferguson, 1984). However, this review will only focus on the calcium effect on textural or mechanical properties.

Calcium content associated with cell wall pectin polysaccharides was observed to affect maximum compression force (i.e. hardness) of blueberry 'Emerald' (firm) and 'Jewel' (softer) during postharvest storage (Olmedo et al., 2021). This relationship may be explained by the effect of calcium on the binding of unesterified pectin and the consequent reduction of cell wall degradation (Angeletti et al., 2010; Olmedo et al., 2021).

The compression test has previously been the preferred test to study the effect of calcium on firmness (Fig. 2). Chord stiffness (Hanson, 1995) or Firmtech firmness (Ochmian, 2012; Vance et al., 2017; Arrington and DeVetter, 2017; Lobos et al., 2021) are the most reported mechanical parameters. However, the use of maximum force to compression has also been reported (Stuckrath et al., 2008; Angeletti et al., 2010). In addition, studies have considered other evaluation methods such as skin toughness by penetration test (Vance et al., 2017) and the texture profile analysis (Olmedo et al., 2021).

One of the most remarkable works on the effect of calcium on blueberry firmness was conducted by Angeletti et al. (2010). The study reported a positive impact of soil calcium (Gypsum, $CaSO_4$) on fruit cell wall calcium content and maximum force to 6 mm compression by a 3 mm diameter flat probe. However, the effect of calcium on mechanical parameters has been highly controversial, mainly when calcium is applied directly to leaves and fruit (foliar application). On the one hand, positive effects on mechanical parameters of using foliar calcium application have previously been reported (Stuckrath et al., 2008; Ochmian, 2012; Lobos et al., 2021). On the other hand, no effect of calcium application was observed (Hanson, 1995; Vance et al., 2017; Arrington and DeVetter, 2017; Manzi and Lado, 2019). Results reported by Lobos et al. (2021) suggested that foliar calcium should be applied at early stages (e.g., fruit set to 16 d after) to affect fruit calcium content and FirmTech firmness.

3.4. *Postharvest management*

3.4.1. *Temperature*

Correct temperature management is the most important postharvest technology for blueberries to decrease fruit metabolism and extend storage life due to water loss and rots reduction. The recommended postharvest temperature to store blueberry is around 0 °C (Nunes et al., 2004; Forney, 2009).

The influence of temperature management after harvest on mechanical parameters has mainly been studied using compression tests with variable equipment choices, including Ametek gauge (Sanford et al., 1991), FirmTech (Tetteh et al., 2004, 2020), and Stable texture analyser (Paniagua et al., 2014). The penetration test has also been considered (Concha-Meyer et al., 2015). In addition, sensorial attributes by mouthfeel (Rosenfeld et al., 1999) and hand-feel (Sanford et al., 1991; Nunes et al., 2004) have previously been used to evaluate the influence of storage temperature.

In general terms, better mechanical parameters are obtained when postharvest fruit temperature is managed below 10 °C (Sanford et al., 1991; Tetteh et al., 2004; NeSmith et al., 2005). However, Forney (2009) reported a higher chord stiffness on blueberries stored at 10 °C than 0 °C when the water vapour pressure deficit was the same at both temperatures (i.e., 0.212 kPa). Similarly, Paniagua et al. (2014) observed higher maximum force to 1 mm compression when blueberries were stored at 4 °C compared to 1 °C, and the water loss was less than 1.5 % at both storage temperatures.

3.4.2. *Relative humidity (water loss)*

As it is affected by the storage temperature and relative humidity, the water vapour pressure deficit is the main environmental driving force leading to blueberry transpiration (water loss) during postharvest (Paniagua et al., 2013). Consequently, high relative humidity (>95% RH) complementing cool storage is the most recommended strategy to retain a low water loss rate (Paniagua et al., 2013; Moggia et al., 2016; Rivera et al., 2021a).

Water loss affects the fresh net weight of a blueberry package (i.e., clamshell) and also induces other quality issues such as expression of shrinkage, shrivel and softening (Nunes and Emond, 2007; Paniagua et al., 2013; Moggia et al., 2016; Rivera et al., 2021a). The effect of water loss on blueberry softening is mostly explained by decreasing the internal turgor pressure (Giongo et al., 2013; Paniagua et al., 2013). In addition, cellular morphology, such as the thickness of the most external cellular layers, has also been related to changes in water loss and mechanical parameters (Li et al., 2021).

The relationship between water loss increase and mechanical changes has mainly been evaluated using a single or double compression test (Ferraz et al., 2000; Li et al., 2021; Moggia et al., 2016; Paniagua et al., 2013; Rivera et al., 2021a,b). However, Rivera et al. (2021a) described that the increase of water loss during storage might be best detected by measuring the displacement at skin break using a needle penetration test, alone or in combination with the reduction of the loading slope (chord stiffness) of a compression test.

On the other hand, if cumulative water loss is minimum (e.g., < 1–2 %) during storage, a firming effect has been detected when evaluating the maximum force to 1 mm deformation (Paniagua et al., 2013) or the loading slope to 15 % deformation (Rivera et al., 2021a).

3.4.3. *Postharvest technologies used to control rot*

Blueberry rots are one of the most critical threats to blueberry quality as they can greatly impact the market life of fresh blueberries (Forney, 2009). Reductions in rot prevalence have been described when using postharvest technologies, including controlled atmosphere (CA) storage (Forney et al., 2003; Harb and Streif, 2004; Alsmairat et al., 2011; Cantin et al., 2012; Rodriguez and Zoffoli, 2016; Falagan et al., 2020), sulfur dioxide (SO_2) (Cantin et al., 2012; Rivera et al., 2013; Saito et al., 2020), ozone (Jaramillo-Sánchez et al., 2019), atmospheric cold plasma (ACP) treatment (Hu et al., 2021), and UV-C light irradiation (Jaramillo-Sánchez et al., 2021).

To test the effect of CA or SO_2 on mechanical parameters, compression test methods have been previously conducted using texture analysers (Schotsmans et al., 2007; Cantin et al., 2012; Rivera et al., 2013, 2022; Paniagua et al., 2014; Falagan et al., 2020), the FirmTech (Forney et al., 2003; Harb and Streif, 2004), the Shore durometer type 00 (Alsmairat et al., 2011), or the Durofel (Chiabrando and Giacalone, 2011; Rodriguez and Zoffoli, 2016). In addition, the penetration test has also been considered to assess the effect of CA (Forney et al., 2003; Duarte et al., 2009; Concha-Meyer et al., 2015; Rivera et al., 2022). The effect of ozone (Concha-Meyer et al., 2015; Jaramillo-Sánchez et al., 2019), ACP (Hu et al., 2021), and UV-C light (Jaramillo-Sánchez et al., 2021) have been studied using the penetration test alone (Fig. 2).

Among the postharvest technologies, storage in CA with high CO_2 (typically > 10 kPa), SO_2 fumigation, or prolonged ACP exposition (i.e., 20 min) has previously been reported to produce adverse effects on mechanical parameters, depending on the cultivar and the storage duration (Allan-Wojtas et al., 2001; Forney et al., 2003; Schotsmans et al., 2007; Duarte et al., 2009; Cantin et al., 2012; Rivera et al., 2013; Hu et al., 2021; Rivera et al., 2022; Rodriguez and Zoffoli, 2016). Conversely, the use of CA had also shown positive retention or increase of mechanical properties of stored blueberries when $O_2 + CO_2$ was set at 20 kPa + 10 kPa (Paniagua et al., 2014), 5 kPa + 10 kPa (Falagan et al., 2020) or 4 kPa + 5 kPa (Rivera et al., 2022).

4. Standardisation of firmness evaluation

This section will summarise the studies contributing to the optimisation of mechanical methods to evaluate blueberry firmness (Table 4). This section also will describe the previously reported relationship between sensory textural and mechanical parameters (Table 5). The sensory descriptor of crispness will also be addressed due to its importance in influencing consumer acceptability (Blaker et al., 2014). Finally, discussion about the use of texture profile analysis to imitate sensory descriptors of blueberry is provided.

Table 4
Summary of the studies contributing to the development or optimisation of mechanical methods or instruments to evaluate blueberry firmness.

Mechanical test	Instrument	Main contributions	Reference
Compression	Instron universal testing machine (UTM)	Use of chord stiffness (g cm^{-1}) to measure blueberry firmness	Ballinger et al. (1973)
Compression	Instron UTM and a blueberry compression instrument (BCI)	Firmness can be determined by measuring the chord stiffness (N m^{-1}) to 25% deformation using a Instron UTM; The BCI allows measuring the time to reach 2 mm deformation that can be used to evaluate firmness; A sample size of approximately 28 berries estimates the population mean by a small deviation	Slaughter and Rohrbach (1985)
Compression	Ametek force transducer	Optimisation of an Ametek device to be used as a low-cost evaluation method of blueberry stiffness	Rohrbach and Mainland (1993)
Compression	Portable firmness measuring device	Development and evaluation of a compression device for cherries and berries. This prototype provided the basis for the commercial FirmTech 2 (Lu and Abbott, 2004)	Timm et al. (1996)
Compression	Instron UTM	Maximum force (N) to < 1 mm deformation of the berry equator obtained by four compression cycles produced smother and consistent force-deformation curves	Ferraz et al. (2000)
Compression	FirmTech 2	A methodology to calculate the apparent modulus of elasticity (Pa) using a FirmTech 2	Prussia et al. (2006)
Compression	FirmTech 2	Modelling of the rate of FirmTech firmness (g mm^{-1}) reduction as influenced by temperature and time	Tetteh et al. (2004)
Compression	FirmTech 2	FirmTech firmness ranges to categorise blueberries as soft (<1.6 N mm^{-1}), moderate (1.6–1.8 N mm^{-1}) and firm (1.81–2.0 N mm^{-1})	Moggia et al. (2017)
Compression	FirmTech 2	A sample size of > 25 berries allows a good estimation of the FirmTech firmness (g mm^{-1}) when evaluating different blueberry genotypes (e.g., phenotyping)	Cappai et al. (2018)
Compression	FirmTech 2 and durometers	Relationship between FirmTech and durometers output data is not strong, especially when blueberries are classified as firm to touch	Moggia et al. (2022)
Penetration	Wagner gram dial GDK 50	First study reporting the use of skin toughness (N) to evaluate blueberry quality	Forney et al. (2003)
Penetration	Stable texture analyser	Estimation of a storage index to compute the changes of mechanical parameters during the storage time	Giongo et al. (2013)
Penetration	Stable texture analyser	Mechanical parameters of distance at skin break (mm) and chord stiffness (N mm^{-1}) provides the best separation of blueberries with different water loss levels	Rivera et al. (2021a)
Penetration	Stable texture analyzer	Mechanical parameter of force at skin break (N) is the best indicators of blueberry maturity	Rivera et al. (2022)
Texture profile analysis (TPA)	Stable texture analyser	First study exploring the use of TPA or double compression on blueberries	Chiabrando et al., (2009)
TPA	Stable texture analyzer	TPA operational settings of 15% strain and 10 s between compression cycles	Rivera et al. (2021b)
Compression and penetration	Stable txture analyzer	Mechanical parameters of chord stiffness (N mm^{-1}) provide good separation of blueberries stored on different atmosphere composition in controlled atmosphere	Rivera et al. (2022)
Compression and penetration	Zwick Roell texture analyser	The most complete profile of mechanical parameters on different blueberry genotypes evaluated up to date	Giongo et al. (2022)
Impact response analysis	BerryBounce	Development and evaluation of a rapid instrumental device (BerryBounce) to assess firmness (i.e., contact time) of raspberries and blueberries	Patel et al. (1993)
Non-mechanical contact deformation	Laser air-puff	Evaluation of a novel instrument to assess the laser air-puff firmness index and springiness index of blueberries	Li et al. (2011)

4.1. *Research contributions to development or optimisation of mechanical methods*

As previously described in this review, instrumental firmness of blueberries has been described using different mechanical parameters: the most recurrent, the maximum force to a predefined compression, and the chord stiffness. However, these parameters have been routinely evaluated using different operational conditions and testing machines.

The main disadvantage of using different methods to measure blueberry firmness is the impedance to comparing and validating results collected either in the commercial blueberry supply chain or within the research community. For example, in reviewing the firmness differences of blueberry genotypes, Cappai et al. (2018) only included the data of the studies that used the FirmTech firmness. This decision was because data obtained using different operational conditions and probe types are not comparable. In addition, more standardised FirmTech firmness data for blueberry genotypes were available than other mechanical methods. This example demonstrates that firmness data's longevity can be at risk if the data cannot be easily used again in the future, or the methods cannot be replicated accurately.

The standardisation of firmness for blueberries will require the selection of a standard mechanical parameter and operational settings such as crosshead speed, target distance, and probe type. The apple is an example of a fruit with a global standard description of firmness

Table 5
Relationship between instrumental mechanical parameters and sensory texture previously reported in blueberry studies.

Instrumental analysis		Sensory analysis		Correlation coefficient (r)	Reference
Machine, test	Parameter	System	Parameter		
Instron Universal testing machine (UTM), plate compression	Chord stiffness	Mouthfeel	Texture during chewing	0.7–0.81	Ballinger et al. (1973)
FirmTech 2, plate compression	Chord stiffness	Mouthfeel	Juiciness Crispness Texture during chewing	0.48 0.44 0.33	Saftner et al. (2008)
FirmTech 2, plate compression	Chord stiffness	Mouthfeel	Crispness Firmness during chewing Skin toughness	0.81 0.85 0.75	Blaker et al. (2014)
Instron UTM, penetration	Bioyield	Mouthfeel	Crispness Firmness during chewing Skin toughness	0.86 0.82 0.78	Blaker et al., (2014)
FirmTech 2, plate compression	Chord stiffness	Mouthfeel	Texture during chewing	0.38	Lobos et al. (2014)
Texture analyser, plate compression[a]	Maximum force	Hand-feel	Finger pressure firmness	0.34	Nunes (2015)[a]
Texture analyser, plate compression	Maximum force	Mouthfeel	Juiciness (succulence)	0.54	Vilela et al. (2016)

[a] This study was conducted by simultaneous compression of a group of blueberries (30 g) rather than individual.

commonly used across research studies and commercial evaluations. Apple firmness is usually measured as the maximum penetration force of the peeled flesh at an equatorial position, using predefined operational settings of penetration distance (7.9 mm depth) and probe type (11.0 mm Magness-Taylor probe) (Musacchi and Serra, 2018). This firmness standardisation has facilitated the provision of consistent quality data between growers and seasons and enabled optimisation of breeding program outcomes and development of suitable pre-and postharvest management, such as harvest timing and storage technologies (Abbott, 1999; Lu and Abbott, 2004; Musacchi and Serra, 2018). Hence, having a standard methodology will shorten the developmental time of new technologies. New management practices can be adopted as lessons can be extracted from data produced globally.

Several studies have provided valuable contributions to the development and improvement of mechanical methods or instruments to evaluate blueberry firmness. The most significant contributions are summarised in Table 4, with the main inferences being summarised as:

1. Different mechanical tests and testing machines (prototypes or commercially available) have been developed and evaluated.
2. The mechanical parameters of compression tests of maximum force and chord stiffness (or FirmTech firmness) were the most evaluated, modelled or optimised parameter.
3. Operational settings such as compression distance and fruit position during compression can produce different results.
4. To develop a firmness standard, the method must be informative of the quality independent of the factors or mechanisms inducing firmness differences.
5. A sample size ≥ 30 berries may be used to evaluate the chord stiffness or the FirmTech firmness with minimum error.
6. To date, there is not a universally accepted standard for measuring blueberry firmness as a quality response.

4.2. Relationship between mechanical and textural properties

Due to the subjectivity of human senses, the food industry prefers instrumental methods rather than sensory descriptors to assess the quality of their products. However, the chosen instrumental method should best represent human sensation and food preferences to rely on the mechanical technique as a form of a reliable measure of quality. Consequently, analysis of the relationship between large and trained sensory panels and instrumental parameters may be used to facilitate the standardisation of cost-effective instrumental methods (Kemp et al., 2009).

Correlations between sensory descriptors of food oral processing and instrumental methods have previously been described on blueberries, with correlation coefficients ranging from weak (r = 0.33) to strong (r = 0.86) (Table 5). The variability between the coefficients can be observed even for the same combination of instrumental and sensory evaluation methods. For example, sensory score during chewing was poor (Saftner et al., 2008; Lobos et al., 2014) or strong (Ballinger et al., 1973; Blaker et al., 2014) correlated with instrumental chord stiffness (Table 5). We hypothesize that reported differences could mainly be attributed to the blueberries samples (e.g., genotypes) and the subjectivity of the sensory methods used in each research study.

Instrumental mechanical parameters used to correlate with sensory descriptors mainly utilise a compression test (Table 5). Consequently, knowledge of whether other mechanical test methods, such as needle penetration and impact response, have a better relationship with sensory evaluation remains unknown. In addition, to assist blueberry breeding programs, commercial grading operations, and quality control, it would be beneficial to determine quantitative threshold ranges of instrumental parameters that can be used as a 'rule of thumb' when related to consumer preferences. Furthermore, as much as the texture variability increases in terms of genotypes expression, a wider range of descriptors should be set to dissect texture complexity more precisely.

It is quite possible for some mechanical parameters that changes in a specific measured range are inconsequential for the consumer experience, while other measured ranges are critical sensory experience indicators. As an example, for kiwifruit, significant softening occurs between harvest (approximately 60–80 N) to when they are considered edible (approximate at 6–8 N) (McAtee et al., 2015). However, improvements in firmness in the 60–10 N range are irrelevant for consumer acceptability because the fruit is not edible in this range. Conversely, kiwifruit can also be considered oversoft at approximately < 5 N, and hence the detection of a 6 N firmness from a 4 N firmness fruit can be regarded as commercially very important. Similar quantification of how soft is too soft or, conversely, how a firm blueberry is firm enough for consumer acceptance is required for the blueberry supply chain.

A complicating and interesting factor in the consumption of blueberries is that due to the small size and ease of hand manipulation, blueberries are often handled (from clamshell to mouth) immediately prior to consumption. Hence, hand-feel touch may also be an essential instance in the judgement of blueberry quality (Table 1). In addition, hand-touch firmness has been reported to be used in commercial operations (Schotsmans et al., 2007; Cantin et al., 2012; Rodriguez and Zoffoli, 2016). The relationship between hand-touch firmness by sensory panellists and instrumental parameters seems like an opportunity to identify instrumental methods to assess blueberry quality related to consumer acceptability. Among the studies reported in this review, only Nunes (2015) reported a correlation coefficient (r = 0.34) between hand-touch firmness and maximum force to simultaneous compression of a group of berries (Table 5). However, the study was conducted using trained individuals rather than a formal sensory panel setting. Whether this reported relationship can be improved by considering sensory panels or other instrumental mechanical methods remains to be studied.

Another interesting point about blueberries compared to other fruits such as apples and kiwifruit is that they can be purchased in bulk and potentially consumed in multiple numbers (2–5 fruit at once) rather than as individual fruit. This fact raises questions about how to handle, analyse, and interpret the firmness data when blueberries are manipulated and consumed as a group (i.e., 2–5):

(1) Does the presence of a single soft berry out of a group (i.e., 2–5) negatively impact consumer acceptance?
(2) Is firmness to be averaged, or should the distribution of firmness in a specific range (e.g., first quartile range) be considered more useful for consumer acceptance?

Consequently, it is worth studying if the mechanical test that allows analysing a group of blueberries simultaneously, such as the Kramer shear test (Makus and Morris, 1993; Silva et al., 2005) and compression of a group (i.e., 30 g) of blueberries (Sanford, 1991; Nunes, 2015; Ktenioudaki et al., 2021), are better representative of sensory properties of bulk blueberry consumption or manipulation in hand.

This review has provided a summary of true non-destructive (non-invasive) techniques related to mechanical parameters (Table 3). Up to date, studies in non-invasive methods have not considered the statistical relation to sensory texture, which is required to understand the strengths of these techniques to segregate blueberries based on consumer sensory acceptability.

4.2.1. Blueberry crispness

Among sensory descriptors, special attention has been given to crispness (Table 1). It is well known that the consumer satisfaction experience when eating small fruit commodities such as cherries (Hampson et al., 2014), grapes (Giacosa et al., 2015), and blueberries (Blaker et al., 2014) can be positively influenced by offering fruit with predominant crispness sensory attributes. Sensory crispness is associated with freshness and is often evaluated using touch and hearing senses when biting or suddenly fracturing a fruit sample (Saftner et al., 2008; Hampson et al., 2014; Giacosa et al., 2015; Vilela et al., 2016). Alternatively, the crispness of blueberries can be described from a sensory point of view as an audible grape-like pop in the mouth when breaking the blueberry skin during the initial mastication or the experience of eating celery stalks (Gilbert et al., 2014).

The relationship between sensory crispness and an instrumental test was previously determined (Table 5). Saftner et al. (2008) observed a positive but weak (r = 0.44) correlation between crispness and FirmTech firmness. In contrast, Blaker et al. (2014) observed a more robust correlation (r > 0.8) between sensory burst energy (crispness) and mechanical parameters of chord stiffness (N mm^{-1}) and bioyield force (N). These strong correlations were obtained using southern highbush cultivars with predetermined crispness differences (crisp VS standard texture genotypes). In addition, Cappai et al. (2020) identified genetic markers partially associated with phenotypic variance in fruit FirmTech firmness in 237 genotypes derived from the cross between two crisp highbush cultivars 'Sweetcrisp' and 'Indigocrisp'. Further study is required to determine whether the relationships between crispness and mechanical data are consistent when using diverse blueberry genotypes and growing conditions.

Alternative instrumental methods to evaluate crispness include combining mechanical and acoustic techniques reported in grapes (Giacosa et al., 2015) and apples (Piazza and Giovenzana, 2015). An acoustic envelope detector can be connected to a testing machine (i.e., texture analyzer) to record the acoustic response through instrumental rupture mechanics (Giacosa et al., 2015; Piazza and Giovenzana, 2015). For blueberries, as far as the authors found, no studies have considered the use of combined acoustic and mechanical parameters to evaluate blueberry crispness. Hence there is room for exploration of these methods in blueberry studies.

4.2.2. Texture Profile Analysis and sensory descriptors

The main benefit of using TPA to characterize fruit produce is the potential relationship to sensory descriptors. However, the descriptors obtained by TPA are mechanical parameters and not sensory properties (Rivera et al., 2021a). Up to date, no studies have related TPA parameters with sensory evaluations of fresh blueberry, and the relationship with sensory parameters cannot be directly extrapolated from previous evaluations obtained for other fruit commodities such as peaches (Contador et al., 2016). In addition, a blueberry deformation of 15 % or 30 % strain, previously used to measure TPA parameters in blueberries, does not generally produce a visible fracture of the berry as chewing between molars does (Rivera et al., 2021a). Hence, the relationship between TPA and sensory parameters should be considered in future blueberry studies. Careful interpretation of the relationship between sensory and TPA results is required, due to the moderate to strong correlation between TPA parameters of cohesiveness, resilience, and hardness, as reported in different blueberry studies (Hu et al., 2015; Xie et al., 2018; Rivera et al., 2021a; Giongo et al., 2022).

5. Conclusions and future research opportunities

Although the research community and commercial supply chain do not have a universal standard method to characterise blueberry firmness, mechanical parameters obtained from a compression test have provided quality characterisation as influenced by pre and postharvest factors. However, important variability in the reported methods, which affect the results, including the testing machine, probe type, target deformation, and calculation procedures from the compression-deformation curve, were found in this review. Consequently, the standardisation of operational settings should be considered, as described by different studies presented in Table 4. In addition, we cannot ignore the fact that the evaluation methods may need to vary if the data is collected for research or commercial purposes, as each of these settings has different constraints that require different decisions to balance ease of data capture, cost, and accuracy of the resulting data.

Mechanical tests other than compression tests have also been used on blueberries, with the penetration test being the second most reported. This test has provided differentiation of berries as influenced by genotype differences (Giongo et al., 2022), maturity (Rivera et al., 2022), storage time (Giongo et al., 2013), storage water loss (Rivera et al., 2021a), and postharvest controlled atmosphere conditions (Forney et al., 2003; Rivera et al., 2022). However, whether the penetration test can provide better results than the compression test to evaluate quality changes remains to be studied. In addition, this review cannot discard the fact that determining a standard for quality characterisation may require a combination of mechanical test methods as described by Rivera et al. (2021); (2022) and Giongo et al. (2022).

True non-destructive methods (non-invasive) have shown promising results relating to blueberry mechanical parameters. Future studies will hopefully further explore how different causes of mechanical changes (e.g., water loss, cell wall properties) can affect instrumental data to ensure that the correlative results produced to date are reproducible across different scenarios.

The relationship of collected instrumental mechanical parameters to sensory texture scores should dictate the value of the collected data. These relationships have to date only been determined considering sensory parameters by mastication. However, hand-touch firmness seems more suitable to imitate how consumers potentially first interact with, and hence infer about, blueberry quality before being consumed (i.e., compression between fingers). Whether the mechanical methods and non-destructive methods described in this review relate to hand-touch remains unknown and is worth investigating.

CRediT authorship contribution statement

Sebastian Rivera: Conceptualization, Visualization, Writing – original draft; **Lara Giongo**: Conceptualization, Writing – review & editing; **Francesco Cappai:** Conceptualization, Writing – review & editing; **Huub Kerckhoffs**: Writing – review & editing; **Svetla Sofkova-Bobcheva**: Writing – review & editing; **Dan Hutchins**: Writing – review & editing; **Andrew East**: Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.postharvbio.2022.112016.

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