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Mechanical properties of kiwifruit as influenced by water loss, location, and compression velocity with respect to compression damage

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ABSTRACT

International distribution of kiwifruit to overseas markets often results in high loads being applied to the fruit for a prolonged time. These high loads may cause compression damage. Compression damage refers to the permanent deformation of near-surface tissue. Kiwifruit affected by compression damage are less attractive to consumers and might result in further deterioration of the fruit. Previous research has been done to model the behaviour of kiwifruit under compression loads and predict compression damage susceptibility. Nevertheless, there is limited understanding of the influence of fruit water loss, compression location and velocity on kiwifruit mechanical properties. In this article, we demonstrate that Young modulus decreases 10-fold during kiwifruit storage (from about 3 MPa to 0.3 MPa). Additionally, kiwifruit of the same flesh firmness and different water loss can present a 2-fold difference in Young's modulus value, with lower values towards the higher water loss. Furthermore, small increase in compression velocity (0.01–0.08 mms^{-1}) led to 2-fold decrease in Young's modulus values. Also, the stem end was found to have a slightly but significantly higher Young's modulus value than the middle of the fruit and the blossom end for soft fruit. These dependencies prove the complexity of the kiwifruit compression damage behaviour and the importance of improvement of the currently existing models.

1. Introduction

Kiwifruit international export supply chains require fruit to withstand weeks or even months of storage. The extended storage makes the fruit more vulnerable to compression damage. This type of damage causes deformation of the fruit surface, and a soft patch in the compression area (Davie, 1997). Soft fruit, including soft patches, are recognised as the primary defect in the kiwifruit supply chain (Zespri, 2023). Compression damage occurs when the applied compression pressure overcomes the yield stress and as a result, the tissue experiences non-recoverable plastic deformation (Zhu, 2024). On a cellular scale, this type of deformation was related to the sliding of fibrils in the cellulose network of the cell wall (Zhang, 2021), and the reduction in intercellular spaces (Calbo et al., 1995). The magnitude of plastic deformation will depend on the ripeness i.e. firmness (Huang, 2022) and water loss of the fruit i.e. turgor pressure (Harker, Hallett, 1994).

Kiwifruit's mechanical properties, i.e. Young modulus, enable modelling its response to compression in different storage scenarios. Several experiments have been conducted to measure kiwifruit mechanical properties (Tian, 2017; Huang, 2022; Li, 2023; Zhu, 2024), but there are high inconsistencies between the reported data. Despite studying different cultivars, Li (2023) and Zhu (2024) reported comparable Young's moduli for the peel (11.2, 10.23 MPa), flesh (2.2, 2.3 MPa) and columella (4.2, 4.5 MPa), indicating that 'Hayward' and 'Xuxiang' kiwifruit withstand similar compression loads. However, different measurement velocities (0.02 mms^{-1} and 0.05 mms^{-1}, respectively) could influence obtained Young's modulus values. Tian (2017) reported similar Young's moduli for the peel (12.04 MPa), but higher for flesh (4 MPa) and columella (5.3 MPa) using 0.08mms^{-1} velocity. Huang (2022) used the same velocity as Tian (2017) and the same cultivar as Li (2023) for different ripening stages. However, none of the measured properties overlapped with the predecessors. The observed differences could be due to biological variation, but we speculate that they are more likely caused by different ripeness stages, water loss and measurement velocity. Although the flesh firmness was not reported in all the studies, the relationship between Young's modulus and failure stress of kiwifruit flesh indicates that it was greatly different (Fig. 1a). Excluding Tian (2017), Young's modulus (Fig. 1b) and flesh failure (Fig. 1c) seem to decrease with increasing measurement velocity. However, this decrease is not definite and could be a result of different

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ripeness.

It was shown that the bruised area for strawberries is highly dependent on the velocity of the compression in the 2–6 mms^{-1} velocity range (Ansar, 2022). Higher velocity caused a higher percentage of damaged tissue for the same strain. Stropek (2022) observed that, for apples, Young's modulus significantly increases not only between steady (0.01 mms^{-1}, 0.1 mms^{-1}, 1 mms^{-1}) and impact compression (400 mms^{-1}, 700 mms^{-1}, 1000 mms^{-1}) but also with small velocity increments within steady compression.

Okaniwa (2022) documented that deformation of ripe kiwifruit (*A. chinensis* cv. Zespri SunGold) under constant force varies by location and changes during storage i.e the deformation increased in the equator area, followed by the blossom end, while remaining almost constant at the stem end. This increase in the deformation under constant force can be understood as a decrease in Young's modulus. However, measurements were conducted only on very soft ready-to-eat fruit; these fruit are not intended for long-term cold storage. Therefore, the understanding of the dependence of Young's moduli on location on kiwifruit surface remains incomplete.

In response to the identified gaps in knowledge, this work will evaluate kiwifruit mechanical properties at equatorial, blossom and stem regions by compressing fruit of a range of firmness and water loss with 0.7 N force at 5 different velocities (0.01, 0.04, 0.08, 0.14, 0.2 mms^{-1}). Although velocity-dependent behaviour has been documented before for other fruits, the significance of the compression velocity on kiwifruit mechanical response has not been previously documented. The aim of this study is to observe and document the mechanical behaviour of kiwifruit as affected by its firmness, water loss, compression velocity and location. This documentation will provide means for development of more sophisticated models of kiwifruit mechanical damage prediction in long-term storage scenarios.

2. Conceptual model of parameters influencing compression damage occurrence during storage

Kiwifruit susceptibility to damage depends on cultivar-specific biomechanical parameters such as elasticity, viscosity, and plasticity (Li, 2017). Elasticity allows the accumulation of energy in the form of deformation. Viscosity resists the flow, attenuating and delaying the deformation movement. Plasticity allows permanent deformation and structure rearrangement if the bioyield point is reached. Principally, fruit tissue will deform and slowly, fully, or partially recover to its previous form when the compression force is removed. Generally, the bioyield point is difficult to monitor with confidence in the stress-strain curve for softening fruit due to highly changing mechanical behaviour. On the other hand, the elasticity can be expressed by how recoverable the induced deformation is in the stress-strain graph by monitoring the final deformation. Also, since viscosity causes the delay of the recovery, it can be expressed by the hysteresis loss. These parameters change as the fruit softens.

Zhang et al. (2021) observed that elastic index decreased exponentially with storage and the water loss increased, but no direct comparison between water loss and elasticity was analysed. Rojas (2002) observed the changes of kiwifruit tissue complex modulus with firmness and turgor pressure as affected by the polyethylene glycol solution. Li et al. (2009) observed that during softening of kiwifruit exposed to 1000 ppm of ethylene for 36 h, elasticity progressively reduced, and viscosity increased. Conversely, Teresaki et al. (2001) observed that the viscosity initially increased during an ethylene treatment, but after the treatment stopped, viscosity started to decrease. This inconsistency in the observation of change in viscosity could be attributed to different water loss levels during treatment and post-treatment storage. High water loss causes a decrease in the turgor pressure of the cells likely causing a decrease in the elastic properties of the fruit tissue as well as an increase in the viscosity due to lower free water content. However, a decline in firmness stems from a complex process and a number of parameters could be considered to influence the measurement.

During long-term storage, kiwifruit softening is caused by dissolution of the middle lamella that keeps individual cells together, pectin degradation, solubilisation of hemicellulose and pectin cell wall polysaccharides, reduction in xyloglucan molecular weight, cell wall swelling, and turgor loss (Schroder and Atkinson 2006; Mebatsion, 2008; Fanta et al., 2014). These processes lead to a disintegration of the cell wall which has the highest contribution to the mechanical properties of whole fruit (Harker and Hallett, 1994; Zdunek et al., 2016).

Different tissue zones, such as the outer pericarp, inner pericarp and core will have different cellular structures (Hallett et al., 1992), thus expressing different mechanical behaviour. The core consists of small tightly packed cells and is the firmest, whereas the inner pericarp is much more non-homogenous and is the softest (Jackson, 1997). Moreover, the softening rates of the tissue zones are different and a disparity between the firmness of the tissue zones changes greatly during ripening (Jackson, 1997). From the mechanical point of view, the higher the difference between the core and pericarp, the higher the contribution of the core to an overall response of the kiwifruit to compression. Redgwell (1990) observed that for the 'Hayward' cultivar the softening rate is higher in the outer pericarp than in core tissue, and the inner pericarp generally changes the least. Also, different tissue zones have different water loss characteristics i.e. water in the core has lower mobility (Burdon and Clark, 2001; Burdon et al., 2014), thus, changes in the turgor pressure can vary between the tissue zones.

The changes in the geometry of different tissue zones dictate changes in the mechanical response in different cultivars with location on the fruit. For example, the 'Hayward' cultivar has a big core and proportionally smaller outer pericarp in comparison to the 'SunGold' cultivar. Both cultivars have cores that do not extend to the blossom end of kiwifruit, making it the most deformable point when the core is much stiffer than the rest of tissue.

Softening and water loss occur simultaneously during kiwifruit storage. Therefore, the combined effect of the softening and water loss

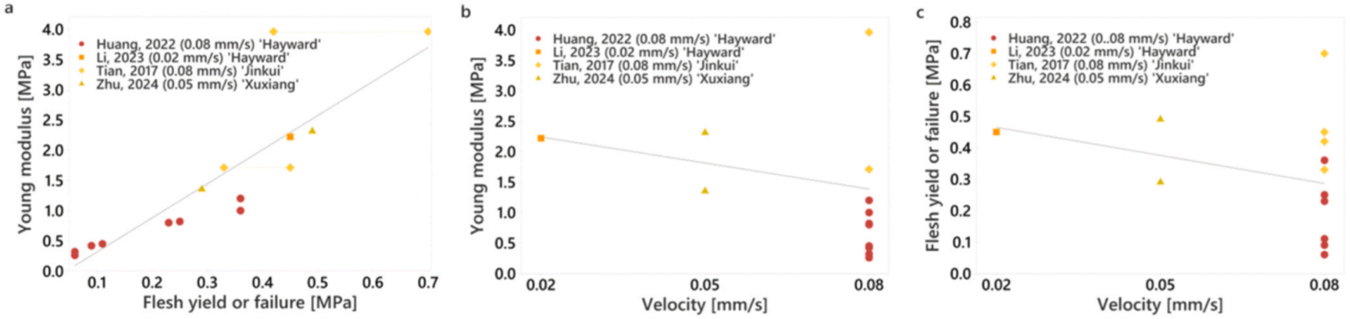

Fig. 1. Relationship between Young's modulus and flesh failure/yield (a), and Young's modulus and measurement velocity (b) in compression testing as observed in different studies.

needs to be considered to evaluate the response of the kiwifruit to compression. Concurrently, these two phenomena are difficult to separate in the experimental conditions.

Based on the previous observations it can be speculated that the resistance to deformation defined by Young's modulus will decrease during ripening due to a decrease in firmness and water loss. Moreover, the viscosity expressed by hysteresis loss will increase and elasticity expressed by degree of elasticity will decrease. Additionally, kiwifruit as a viscoelastic-plastic material will respond differently to compression depending on the velocity/frequency of the applied load, due to the velocity dispersion caused by the viscous behaviour of the fruit. A conceptual diagram of the changes in the mechanical behaviour of kiwifruit is presented in Fig. 2.

Li (2017) emphasized the importance of modelling the mechanical behaviour of unripe fruit and its change during ripening to correctly predict the damage during mechanical handling and transport. For kiwifruit, which change their firmness about 5-fold during storage, modelling of the compression in bulk boxes needs to include the firmness change, water loss and compression location. Such models would allow adjustment of packaging designs at different ripening stages. Additionally, storage temperature conditions might be different depending on the ripeness stage, time to delivery or degreening process (Burdon et al., 2022). Understanding velocity-dependence of mechanical behaviour of kiwifruit provides insight for adjustment of the compression in storage.

3. Experiments and assessment metrics

3.1. Plant material

'SunGold' kiwifruit (*Actinidia chinensis var. chinensis*) were sourced from a commercial packhouse on the 19th of April from one grower source. Fruit were considered class I and in three sizes (151–180 g, 128–138 g, 108–118 g). The different sizes of fruit were chosen to represent the distribution of fruit sizes in the overseas export. Fruit were packed in single-layer trays with liners to avoid initial compression deformation. Fruit free of major defects (i.e., blemish, sunburn, bruising) were weighed with 0.001 g precision (PG503-S, Metter Toledo, USA) and set back into trays for storage at 1℃ (approximately 98 % RH). On arrival, fruit were on average 60 N firm and had 11 % total soluble solids. Fruit of flesh firmness ranging between about 5 – 75 N, achieved by different storage times, were chosen for the experiment. Thirty fruit (10 per size) were evaluated at 2, 5, 8, 10, 14, 16, 20, and 26 weeks postharvest, resulting in a total of 240 fruit. Before each measurement, fruit were warmed up overnight to 20℃. Flesh firmness was assessed at the evaluation timepoint with an electronic penetrometer (Willowbank Electronics Ltd., Napier, New Zealand) fitted with the standard 7.9 mm Magness-Taylor probe. A 1 mm slice of fruit skin was removed, and the flesh was punctured at 8 mms^{-1}, in equatorial positions not previously used for compression measurements. Percentage water loss was obtained by weighing the fruit on arrival and the evaluation time-points. Each evaluation was done within a 4 h period to make sure that there is no influence of other factors (e.g. natural ripening) on the observed differences between the location on the fruit. The measurement with different compression velocity was done within a few minutes on each fruit.

3.2. Compression application

Fruit were compressed using a texture analyser (TA, TA.XT plus, Stable Micro Systems, Surrey, UK) equipped with a 5 kg load cell. A custom-made glass ball probe (25 mm diameter) was used to compensate for the uneven surface of the kiwifruit. For each fruit, five different equatorial positions were compressed with 0.7 N, each at a different velocity (0.01, 0.04, 0.08, 0.14, and 0.2 mms^{-1}). The 0.7 N force was chosen to represent the force that does not cause any damage even to very soft fruit. Also, this force corresponded to a compression force equivalent to the approximate weight of one kiwifruit in a bulk box packaging. The velocities were chosen starting from the lowest achievable velocity of 0.01 mms^{-1} (TA limitation), and regularly spaced increases overlapping previously used velocity ranges. The trigger force was 0.05 N, and the fruit were preloaded to 0.07 N for 5 s, keeping the force constant, before the compression to improve the stability of the measurement. For each fruit, five force-displacement curves corresponding to the five velocities were collected. From the force-displacement curve, Young's modulus (E, Eq. (1)) was calculated using the Hertzian model for a spherical indenter (Mendová et al., 2024):

$$E = \frac{3}{4}\frac{F(1-\nu^2)}{\sqrt{Rd^3}} \tag{1}$$

where F is a force, d is the distance, R is the radius of the ball probe (25 mm) and ν is Poisson's ratio. Poisson's ratio describes the ratio between transverse contraction and longitudinal expansion, for kiwifruit, most widely accepted value of the ratio is 0.3 (Li, 2023; Zhu, 2024; Erukainure et al., 2022; Tian, 2017). Due to a small force applied and a small contact area, the surface of the fruit at the contact point was assumed flat. Young's modulus was determined in the linear region, for 0.7 N force and the associated distance corresponding to that force. Although the Hertz theory for sphere contact with elastic half space has its limitations, such as assuming that kiwifruit is elastic half space and the compression is within elastic limit, it was previously observed that it can still provide correct estimation of Young modulus for small deformation (Kontomaris 2020).

To provide better data for modelling purpose, K-means cluster analysis was done to create 6 clusters with specific firmness ranges, water loss, and Young's modulus for measurement at the equatorial position with 0.01 mm/s compression velocity as the slowest possible measurement in the current study (Minitab® 21.3.1 (64-bit)).

As a viscoelastic material, kiwifruit will express both viscous and elastic behaviour. The viscous behaviour can be assessed by hysteresis

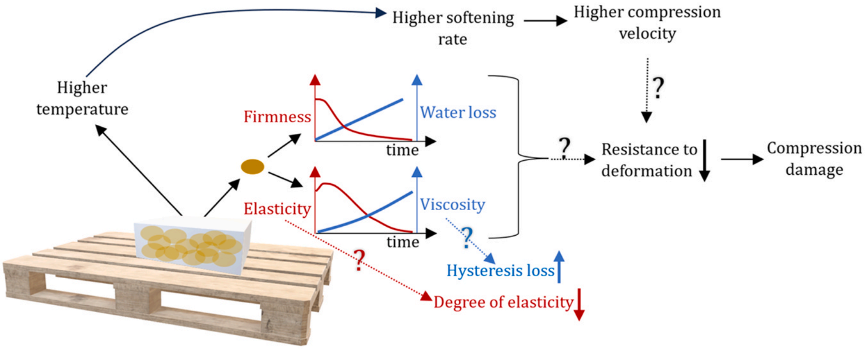

Fig. 2. Conceptual diagram of changes to kiwifruit during long-term storage related to compression damage.

loss and elastic behaviour by degree of elasticity. The hysteresis loss (*HL,* Eq. (2)) and degree of elasticity (*DE,* Eq. (3)) were calculated as follows (Blahovec, 2011):

$$HL = 100 \quad \bullet \quad \frac{W_L - \quad W_{UL}}{W_L} \tag{2}$$

$$DE = 1 - \frac{D_f}{D_m} \tag{3}$$

where W_L and W_{UL} are deformation work during loading and unloading, respectively, calculated as the area under the curves in the force-deformation plot. D_m is the maximum reached displacement and D_f is the final "permanent" deformation achieved by the end of the measurement.

The change of Young's modulus, maximum displacement, hysteresis loss, and degree of elasticity with flesh firmness and water loss were analysed. The Young's modulus and maximum displacement were also compared between the blossom end, stem end and the middle of the fruit for the same data set with the exception of week 26 for which these data were not measured.

A specially designed holder was made to hold fruit in place for different equatorial positions, where the probe was carefully placed in the middle of the fruit. For the stem and blossom ends, another holder was made with a constant angle preventing the sliding of the fruit to obtain a right angle between the fruit surface and the direction of compression. The small curvature of the kiwifruit at contact with the probe was ensured.

For velocity comparison, a smaller data set was chosen due to the limitation of the TA analyser to produce the same force with different velocities. Although the maximum force was set during measurement, the force reached during the measurement varied slightly and showed a velocity-dependent trend (Table 1). This velocity-dependent trend was caused by the limitation of the machine to stop the probe in a short time as the set force was reached. The velocity dependency was more prominent for the firm fruit as the set force was reached with a small displacement, i.e. in a shorter time. Therefore, a small constant force (0.7014 – 0.7024 N) subset from fruit with flesh firmness 4.9 – 19.6 N was chosen for velocity analysis. This subset did not show a significant difference in the force applied as influenced by measurement velocity (Table 1). The constant force subset region (0.7014 – 0.7024 N) was chosen as per the most populated bin in a histogram of forces reached during measurement (Fig. 3). Significant differences were tested using one-way ANOVA and Tukey's method with 95 % confidence (Minitab® 21.3.1 (64-bit)).

4. Results and discussion

As expected, the maximum displacement of the compression probe against the fruit increased (Fig. 4a) and Young's modulus decreased as the fruit softened (Fig. 4b) and lost water (Fig. 4f). The hysteresis loss increased during ripening (Fig. 4c) and water loss (Fig. 4g), and the degree of elasticity decreased (Fig. 4d,h). The change in the degree of elasticity and hysteresis loss is presumably due to the decrease in elasticity and increase in viscosity of the fruit, respectively, as they soften and lose water (Li, 2009). Most changes in the viscoelastic properties seem to start at about 20 N of firmness. The maximum displacement, indentation depth, is mostly below 0.8 mm, which represents a probe radius to indentation ratio of 0.06. This ratio is much smaller than 0.1, the limit for use of the Hertz theory for spherical indenters suggesteb by Kontomaris (2020). Young's modulus values are initially highly variable with a slope equal to 0.003 MPa/N (R^2=0.1 %) and average around 3 MPa until 57 N when it starts to decrease with a slope of 0.03 MPa/N (R^2=15 %). This decrease becomes steep around 21 N (2 MPa) to a slope of 0.099 MPa/N (R^2=58 %) (Fig. 4b). These trends could relate to different softening phases in which different changes in the kiwifruit structure occur. The three phases of kiwifruit ripening are a slow initial phase, rapid softening phase, and slow final phase, for the presented data these softening phases are presented based on a control data set in the Appendix, the initial slow phase might be less prominent in this data as the fruit were sourced from packhouse. In this experiment, the first softening phase finished somewhere around 50 N and the second (fast drop in flesh firmness) around 20 N. The reported range of Young's modulus corresponds well to that previously reported for the kiwifruit flesh (Li, 2023; Huang, 2022; Tian, 2017; Zhu, 2024) but provides more information to the change of the Young's modulus with firmness, which can be implemented into the models.

Table 1
Change of the maximum force with the velocity of the compression for the full data set and a chosen subset corresponding to force between 0.7014 – 0.7024 N for fruit 4.9 – 19.6 N. Significant differences were determined using ANOVA with Tukey's comparison ($p < 0.05$).

	Full data set			*Subset*		
Velocity [mms^{-1}]	**N**	**Mean [N]**	**Group**	**N**	**Mean [N]**	**Group**
0.20	667	0.7400	**A**	26	0.7019	**A**
0.14	663	0.7211	***B***	38	0.7019	**A**
0.08	658	0.7086	***C***	65	0.7019	**A**
0.04	675	0.7039	***D***	116	0.7019	**A**
0.01	665	0.7001	***D***	44	0.7019	**A**

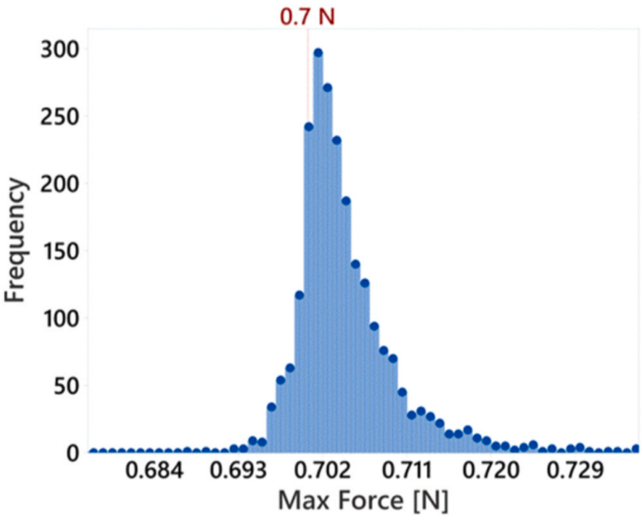

Fig. 3. The distribution of compression force during the Texture analyser measurement (cropped to 0.6769 – 0.7358 N to better represent the maximum).

For the water loss, a more linear increase in the maximum displacement can be observed. There is high variability in Young's modulus in each 0.1 % water loss bin. Average Young's modulus seems to rapidly decrease from around 2 MPa to 0.7 MPa until about 2 % water loss, and then slowly decrease up to about 5 % water loss when it stays approximately constant. An approximately linear increase in hysteresis loss and a decrease in degree of elasticity with water loss is present.

Interestingly, the more drastic change in the mechanical parameters was evident when the firmness reached a slow steady decline (below 20 N flesh firmness), and the water loss increased. It can be observed that, in this experiment, the water loss is high for fruit under 15 N (Fig. 5a), which is most likely due to a lower RH in the trays later in storage. Also, for constant firmness (9.32 – 10.25 N), Young's modulus decreased for fruit with higher water loss (Fig. 5b). The decrease in Young's modulus during ripening in long-term storage indicates a possible 10-fold misinterpretation of the kiwifruit behaviour if changes to kiwifruit during storage are not considered.

K-means cluster analysis showed that for fruit with centroid at 65 N firmness and 0.7 % water loss, 2.7 MPa Young's modulus can be

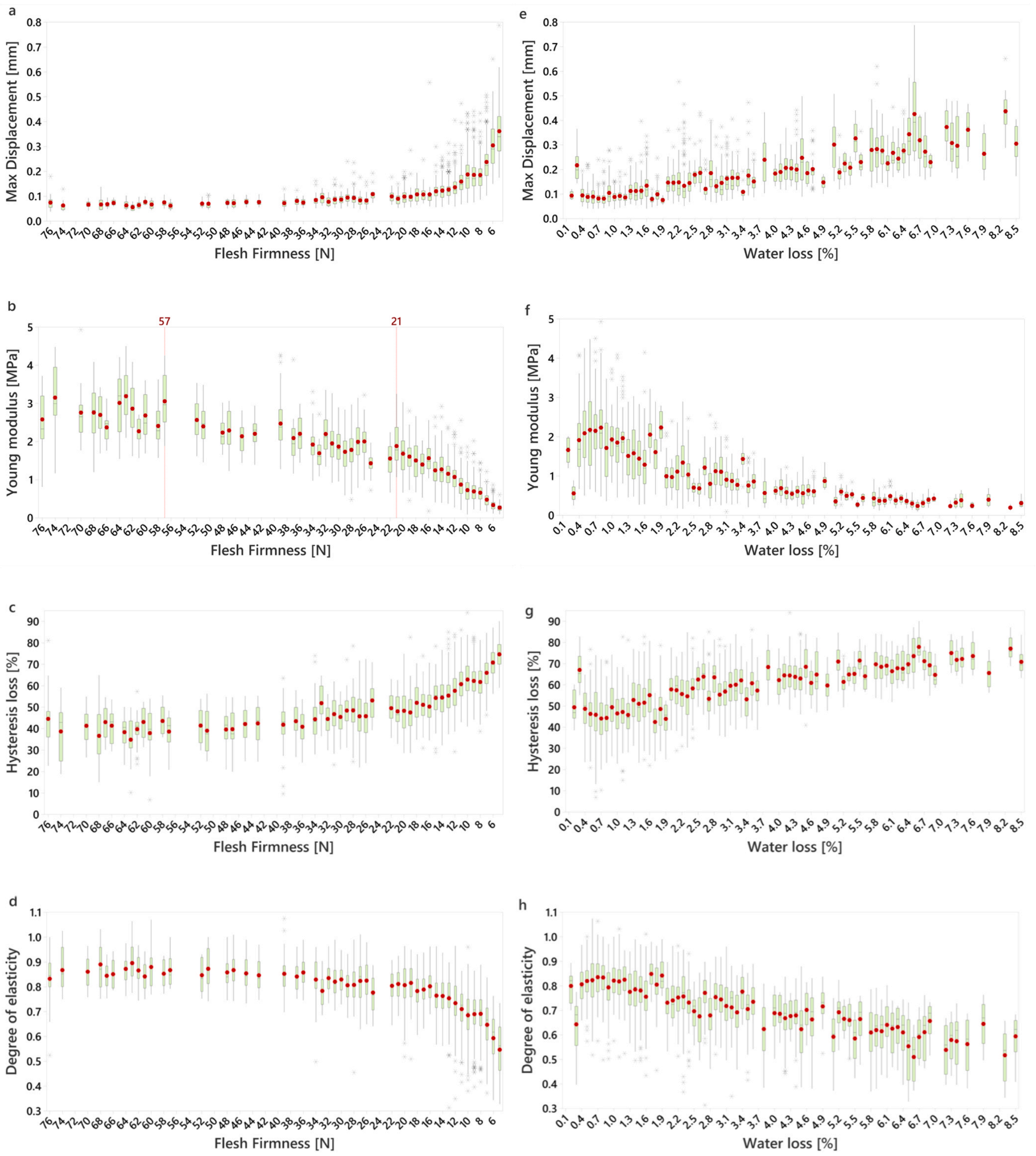

Fig. 4. Box plots representing the change of maximum displacement (a, e), Young‘s modulus (b, f), hysteresis loss (c, g), and degree of elasticity (d, h) with the decline of firmness (a, b, c, d) and loss of water (e, f, g, h). Each boxplot corresponds to data from 1 N or 0.1 % bin and consists of data obtained using 5 velocities at stem-end, blossom-end and equatorial positions. The blue line on graph b indicates the linear trend for three firmness subsets.

expected. Young’s modulus decreases with firmness drop and water loss up to 0.4 MPa for 7 N firmness and 6.3 % water loss (Table 2). The values identified in the clusters allow better prediction of compression behaviour during different stages of the supply chain.

As expected, the equator and blossom ends of the fruit was found to be softer than the stem end when the fruit is soft (5–15 N), this difference is small but significant (Fig. 6). However, it cannot be stated for the firm fruit (>15 N). The difference in maximum displacement for constant force within chosen firmness ranges is also significant between the equator and stem end in the 5 – 15 N range. There is no significant difference between the blossom end and the equatorial position. The obtained differences in deformation and Young’s modulus between locations on kiwifruit surface confirm previous observations made by Okaniwa (2022). The presented location-dependent parameters also

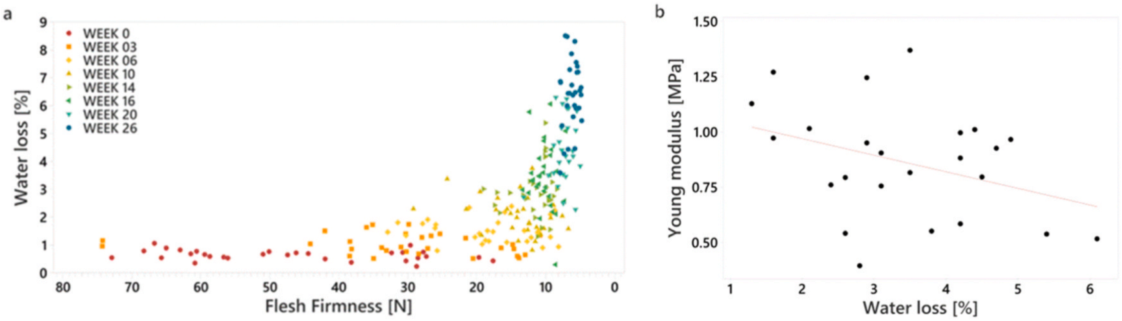

Fig. 5. The relationship between water loss and firmness in the whole dataset (a), and the relationship of Young‘s modulus to water loss in a small firmness range (9.32 – 10.25 N) (b). The uncertainty of the measurement based on the equipment limitation is too small to be shown in the form of an error bar.

Table 2
Six clusters obtained from k-means cluster analysis for measurement at the equatorial position with 0.01 mm/s compression velocity.

Cluster	1	2	3	4	5	6
Firmness [N]	65	42	27	13	11	7
Water loss [%]	0.7	0.8	1.2	1.6	3.5	6.3
Young’s modulus [MPa]	2.7	2.4	1.9	1.1	0.8	0.4

provide the significance of the changes in kiwifruit behaviour with location and shows that the significant difference is only observed for soft fruit (5–15 N).

Although the deformation is applied only to the outer pericarp zone, the stress distribution reaches deeper layers of the fruit due to the differences in properties of the tissue zones. Thus, the proportion of different tissue types in the depth direction could contribute to near-surface deformation behaviour. It is difficult to state if the difference in flesh Young’s modulus at different surface locations is attributed to different properties of tissue in the stem-end and equatorial area, or only the different proportions of the hard, core tissue and the soft flesh. Measuring individual samples of flesh and core from the stem-end and the middle of kiwifruit would help to determine whether different firmness for these zones or only geometry should be included in future models of kiwifruit behaviour under compression.

Estimated Young’s modulus decreased, and maximum displacement increased as measurement velocity rose (Fig. 7) with a significant

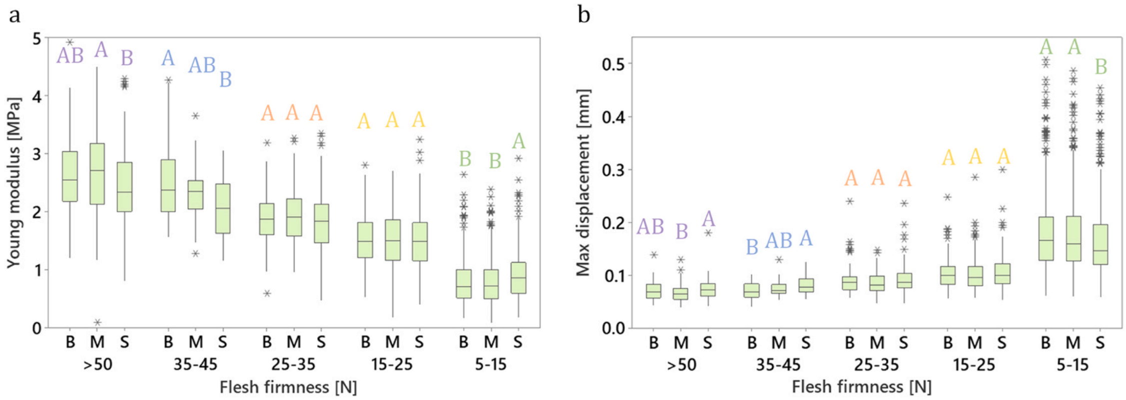

Fig. 6. Young‘s modulus (a) and maximum displacement (b) measured at different locations on the fruit: blossom end (B), middle (M) and stem end (S), and the letters in each firmness range indicate differences after one-way ANOVA and the Tukey’s comparison and 95 % confidence. The smallest group had 45 measurements in each box plot (35–45 N) and the biggest group 579 measurements (5–15 N).

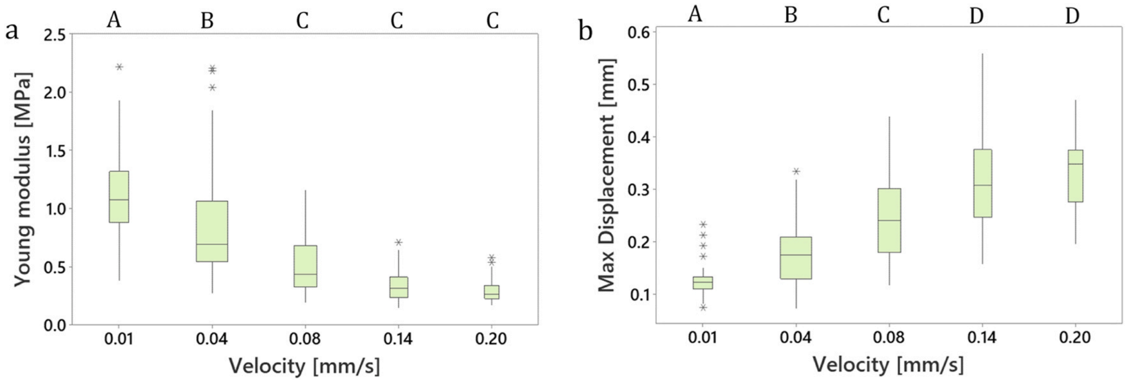

Fig. 7. Change of the Young’s modulus (a) and maximum displacement (b) with compression velocity, and letters indicate differences after one-way ANOVA and Tukey‘s comparison with 95 % confidence. Starting from 0.01 mm/s, group sizes were respectively 44, 116, 65, 38, 26 fruit.

change in 0.01–0.08 mms^{-1} range. An almost two-fold increase was present in this work between 0.08 mms^{-1} and 0.02 mms^{-1} velocities for whole kiwifruit. This is the range in which most of compression damage tests have been done (Tian, 2017; Huang, 2022; Li, 2023; Zhu, 2024). Different velocities used by Tian (2017), Huang (2022), Li (2023), and Zhu (2024) most likely contributed to the differences observed between those studies in Young's modulus values for kiwifruit flesh. Recognising this velocity-dependence of Young's modulus occurs, is important for a better understanding of the compression damage in steady long-storage scenarios and modelling the compression damage susceptibility. Previously, 5 % strain was considered as the damage threshold in kiwifruit (Zhu, 2024). A 2-fold misestimation of Young's modulus value when designing the kiwifruit storage conditions will cause a setting of forces that will induce double the strain related to the damage threshold and will cause much higher losses than originally expected. Thus, the findings from the current work could help to increase the prediction accuracy of fruit mechanical damage by at least 2-fold (in terms of predicted strains).

The importance of velocity on measured fruit mechanical response was highlighted by Stropek (2022) and An et al., 2020 in apples and strawberries respectively, but measurements were done with constant deformation. Thus, velocities will result in a different maximum force of a measurement. This type of experiment does not represent the long-term storage. In long-term storage, the force compressing the fruit is kept relatively constant (neglecting the water loss of fruit), thus, the displacement must increase with the increase in the velocity. This is in agreement with the findings of the current work (Fig. 7b). This higher displacement will correlate with higher observed prominence of compression damage.

As presented here velocity-dependent behaviour shows a significant change in Young's modulus, the velocity of compression in a long-term storage scenario needs to be further analysed as a variable. The velocity of compression in a long-term storage scenario will depend on the load put on the kiwifruit, fruit firmness and water loss of the kiwifruit. High compression velocity will be achieved if the fruit is softer at the time of initial compression and will depend on the ripening rate of the kiwifruit. The faster the fruit ripens, the higher the compression velocity and an increase in Young's modulus with a decrease of velocity should be expected. However, devices used for fruit compression responses have limited observation windows. Observing changes below 0.01mms^{-1} (the limitation of the TA machine used in this work) would help observe if the change of the mechanical properties with velocity comes to a plateau after a certain velocity. This could be achieved using newer models of TA that allow compression with 0.001 mms^{-1} velocity or by observing displacement of a constant load during storage. Alternatively, models projecting the mechanical parameters to a steady compression could be tested. Examples include the generalised Maxwell model (describing stress relaxation) (Li, 2016) and the generalised Kelvin-Voigt model (describing the stress reaction) (Vicente, 2012).

The effect of the force variability was minimised in the presented research. However, another study with slightly higher force would allow for a more constant force scenario as the time of stopping of the probe would increase reducing the force dependability on the velocity of the measurement.

5. Conclusions

This study investigated the influence of fruit quality and storage parameters on the mechanical parameters of kiwifruit i.e. Young's modulus, viscosity, and elasticity. Softening, water loss, compression velocity and location of compression on the fruit surface were all found to be important factors in affecting kiwifruit mechanical behaviour. Therefore, these parameters should be considered as factors in the response of the kiwifruit to compression in long-term storage (weeks of storage). The highest change in Young's modulus, i.e. 10-fold decrease, was caused by softening. Additionally, for the same firmness a 2-fold decrease in Young's modulus value was observed, with a 5-fold increase in water loss as well as with a velocity increase between 0.01 and 0.08 mms^{-1}.

The Young's modulus values presented in the current work can be incorporated into existing Finite Element models to better represent the ever-changing mechanical behaviour of kiwifruit and prediction of compression damage risk.

CRediT authorship contribution statement

Urbanska Magdalena: Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Andrew East:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Mo Li:** Writing – review & editing.

Author agreement statement

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the sole contact for the Editorial process. He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: This research was funded by Zespri® International Ltd and the authors have an ongoing professional relationship them.

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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.2025.113682.

Data availability

The authors do not have permission to share data.

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