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The Effect of Foliar Calcium Spraying on Changes in the Mechanical Properties of Blueberry (*Vaccinium corymbosum* L.)

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Abstract: One of the methods used to improve the durability of blueberry fruits is the application of nutrients through foliar feeding with calcium, which can improve the post-harvest mechanical parameters. This study proposed an optimal selection of calcium spray parameters, which enables a rational minimisation of the negative impact of agrochemicals in the environment. The qualitative evaluation of blueberry fruit showed lime spraying induces a significant effect on the increase in fruit size, especially at a pressure of 0.2 MPa and with AIXR nozzles compared to the control group. To assess the mechanical properties, a modern method of identifying the actual loads and maximum surface pressures generated by the picker during harvesting is presented. Compression and fruit rupture tests were also used to determine the pressure values and forces that are considered safe from the perspective of harvest quality. The comparative analysis of destructive compression and detachment tests confirmed that fruit firmness (Fp) was approximately 80% higher than the detachment force (Fpf), with peak pressures more than twice as high, suggesting that handpicking poses minimal risk of mechanical damage. The implementation of optimal spraying techniques combined with the correct assessment of the mechanical properties of fruits is important in agricultural practice, where it is crucial to obtain high-quality blueberries after harvest.

Keywords: spray technique; fertiliser; firmness; handpicking; compression

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1. Introduction

The quantity of the yield is a key factor in field, fruit, and vegetable production, influencing consumer product choices and agricultural producers' incomes. Practices used during plant growth and development affect both the yield and product quality after harvest and during storage.

To ensure high-quality and abundant yields, it is essential to provide adequate nutrients in the vegetative phase of plants [1–4]. Foliar application of nutrients during the production season can enhance the quality of agricultural produce [5]. Foliar fertilisation is a vital component of sustainable and efficient crop management, as it reduces the use of chemical fertilisers and mitigates environmental hazards. During foliar fertilisation and spraying, it is crucial to establish the optimal technical and technological parameters. This ensures maximum substance absorption by the plant while minimising undesirable side effects associated with the use of agrochemicals.

The growing interest in blueberry cultivation is related to the high market demand for its fruits. Numerous studies have demonstrated their health-promoting, anti-inflammatory, antioxidant and anti-cancer properties [6–8]. In 2023, the largest areas of blueberry cultivation were located in the China, USA, Canada, Chile, Peru, and Poland [9].

Blueberries (*Vaccinium corymbosum* L.) are primarily intended for the fresh produce market and are mainly harvested by hand [10]. The perishable nature of blueberries makes them particularly susceptible to mechanical damage, which leads to economic losses [11]. Blueberry damage is often difficult to detect due to its colour. Non-destructive testing by Hu et al. [12], Yang et al. [13], and Leiva-Valenzuela et al. [14] confirmed that after impact testing, there was considerable difficulty in distinguishing damage in the fruit. Although mechanical harvesting systems are available, they are associated with lower harvest quality [15,16]. Blueberries have a relatively thick, waxy skin, but subcutaneous damage in the form of bruises occurs in over 70% of mechanically harvested blueberries, making them unsuitable for long-term storage and fresh consumption [17,18]. When harvested manually, losses are minimal (up to 22%) [19], but post-harvest processes such as transportation, handling, and storage can increase ethylene production and decrease blueberry firmness [20].

One method to extend the shelf life of blueberries is foliar fertilisation with calcium, which can enhance mechanical parameters after harvest. Calcium strengthens the rigidity of cell walls and has a beneficial effect on fruit storage through the reduction of the respiration rate, ethylene synthesis, protein breakdown, mass loss, and post-harvest degradation. The beneficial effects of calcium on maintaining fruit quality and extending shelf life have been documented by many researchers, including Moradinezhad et al. [21] in apricot cultivation; Cieniawska et al. [22], Singh et al. [23], and Sidhu et al. [24] in strawberry cultivation; as well as Lobos et al. [25] and Bilbao-Sainz et al. [26] in blueberry cultivation; and Abrol et al. [27] in peach cultivation.

The quality assessment of harvested fruit is based on firmness tests, which are a key parameter for fresh blueberries. Researchers working with blueberries have not yet identified a universal standard method for assessing firmness for quality purposes [28,29]. For small, soft berries, firmness is often assessed by measuring the deformation under constant load through instrumental penetration or compression tests [30–33]. Standard compression probes (flat-surfaced plates) are often used to conduct the parallel compression of the fruit contact surface [34]. A common requirement is that the loading plate is larger than the fruit contact surface to facilitate an evaluation of the compression mechanics. It should be noted that due to differences in the parameters and measurement methods used, compression test results will vary [35,36].

Upon reviewing the available literature, the authors decided to propose an effective method for measuring firmness that combines the synchronous compression method with surface pressure measurement techniques, which have not yet been used to assess the quality of blueberries. Studies conducted on other fruits have yielded promising results, both in terms of the originality of the method and the accuracy of the data obtained [22,37]. In addition, the assessment of surface pressures provides further insights into the strength parameters occurring during field harvesting and laboratory compression, allowing for a better comparison of results.

The aim of this study was to evaluate the impact of the spray technique used for calcium-based treatment on changes in the mechanical properties of blueberry fruit, which determine the quality of hand-harvested blueberries.

2. Materials and Methods

2.1. Experimental Set-Up

The research was carried out in two stages as follows: in the first stage, biological material was collected during field tests, followed by laboratory tests, conducted according to the plan outlined in Figure 1:

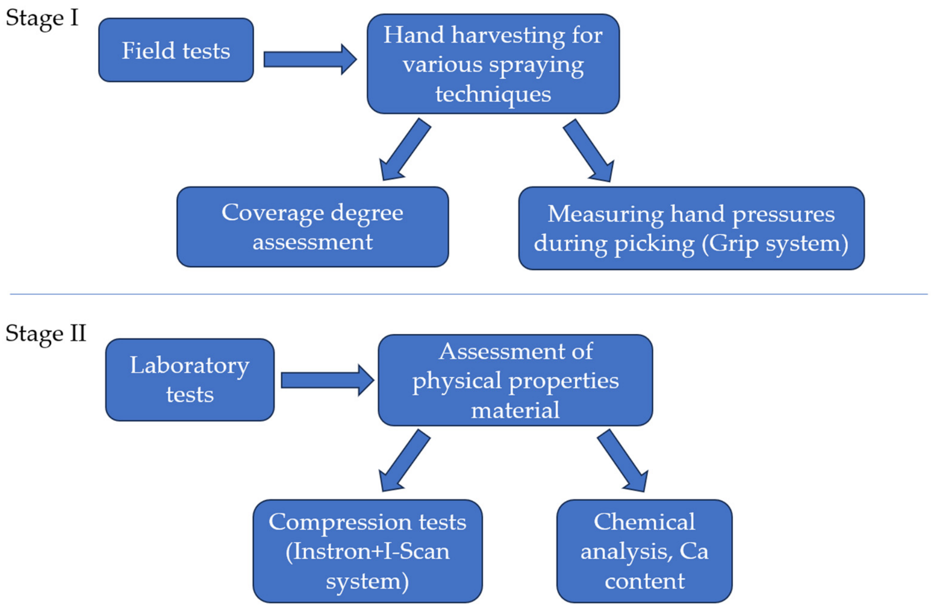


Figure 1. Research plan.

The study was conducted on a Duke blueberry plantation located in Szczodrów, Syców Municipality, Poland (51°16′42.421″ N, 17°33′18.368″ E). The experiments followed a randomised design with nine treatments and two replications. The experimental area consisted of two 50 m rows, which were divided into 10 m sections. Each plot (experimental unit) consisted of 11 bushes, spaced 1m apart. Each row was 1.5 m wide, with a 2 m distance between rows. The treatments were a combination of three factors plus an additional control treatment. The tested factors were sprayer driving speed (2.5 km h^{-1} and 5.5 km h^{-1}), spraying pressure (200 kPa and 400 kPa), and nozzle type (standard XR and air induction AIXR). The cultivation site was as follows: The substrate consisted of a mixture of peat, pine bark, and manure. The plantation was fertigated, and the soil pH was 4.5. The *Duke* variety is known for its high yield and rapid growth, reaching a height of up to 180 cm. The fruits vary in size, are juicy, and have a sweet-tart flavour. This variety is one of the earliest ripening blueberry varieties, with a long fruiting period. It blooms late, after the spring frosts have passed.

Fertilisation was applied twice, on 8 May and 22 May 2024. Foliar fertiliser application was carried out in the following weather conditions: air temperature 17–20 °C, relative humidity 60–65%, and wind speed 1 m s^{-1}. Fertilisation was performed at the onset of fruit maturation. Figure 2 shows the test set-up test stand.

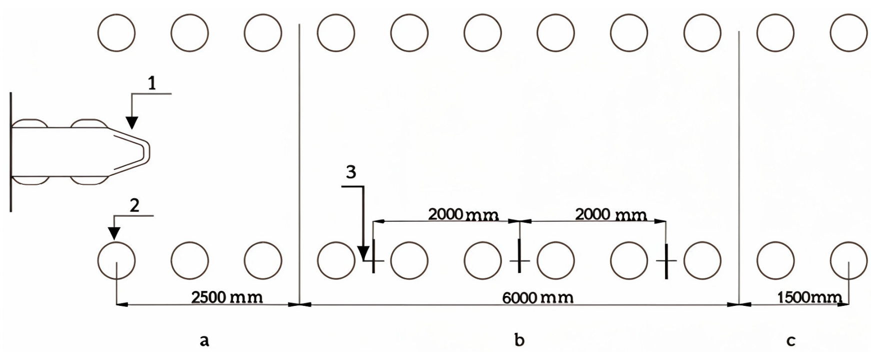


Figure 2. View of the test set-up: 1, Sprayer; 2, blueberry bush; 3, support with water sensitive paper; (**a**), inrun section; (**b**), measurement section; (**c**), final section.

Fertilisation was carried out using a calcium-containing product from Tessenderlo at a rate of 10 L ha^{-1}. Spraying was performed using standard flat fan XR 11003 nozzles and air induction flat fan AIXR 11003 nozzles. The following spraying conditions and nozzle parameters were applied:

- Driving speeds—2.5 km h^{-1} and 5.5 km h^{-1};
- Liquid pressure—0.2 MPa and 0.4 MPa;
- Sprayer boom height—0.5 m.

Before each pass, the air temperature and humidity were measured, and the liquid flow rate from the nozzles was monitored. To determine the flow rate, the liquid was collected in a graduated cylinder. The measurement time was 1 min. The collected volume was then read and compared to the value provided by the nozzle manufacturer. If discrepancies were observed between the measured value and the catalogue value, the liquid pressure was adjusted accordingly.

2.2. Degree of Coverage of Sprayed Surfaces

The coverage of sprayed surfaces was analysed using water-sensitive paper samples (WSP; 76 mm × 26 mm; Syngenta Crop Protection AG, Basel, Switzerland). The samples were attached to supports to cover both vertical and horizontal surfaces. The areas of contact of the water-sensitive paper with the liquid turned a dark blue.

Each experimental section contained three supports with water-sensitive papers (WSP), allowing the experiment to be conducted in three replicates. The first support was placed 3 m from the start of the section, and the remaining two were placed 2 metres apart. After spraying, the water-sensitive papers (WSP) were removed from their supports, attached to pre-prepared templates, and secured against moisture after drying. The papers were then scanned, and the analysis was conducted using Adobe Photoshop (22.0) 2021 (Adobe Inc., San Jose, CA, USA). During the analysis, three random sections of 1 cm^2 were selected from the WSP surfaces. To calculate the coverage of the sprayed surfaces, the number of pixels for the analysed sample was recorded, as well as the number of pixels for the areas covered by the liquid. The coverage was calculated as the ratio of the number of pixels in the liquid-covered area to the total number of pixels in the entire analysed area (Formula (1)).

$$P_{sp} = P_{pc} \cdot {P_a}^{-1} \cdot 100\ [\%] \quad (1)$$

where

P_{sp}—is the percentage coverage of the each surface;
P_{pc}—is the area covered by liquid in pixels;
P_a—is the analysed area in pixels.

No horizontal bottom surface coverage was observed during the study, and therefore, it was not included in further analyses.

The total coverage was then calculated as the sum from all three surfaces (vertical approach surface, vertical leaving surface, and horizontal upper surface).

2.3. Calcium Content in Fruits

To determine the calcium content in fruits, measurements were conducted using flame photometry (Jena Model III, Zeiss, Poznań, Poland). The advantages of the flame photometry method are as follows:

- Good sensitivity and detectability;
- Satisfactory accuracy and precision;

- High speed of single determinations. The experiments were carried out at the Department of Horticulture, Wrocław University of Environmental and Life Sciences, according to the procedure described in [22].

To quantify the calcium content, the material was first dried at 105 °C, ground, and sieved through a 1 mm laboratory sieve. Subsequently, 0.4 g of air-dried plant material was weighed. The prepared samples were transferred to containers and 2% acetic acid was added. The samples were then shaken for 30 min on a laboratory shaker at a frequency of 150 revolutions per minute. The resulting suspension was filtered through a medium quantitative filter (Chemland). After filtration, flame photometry readings were taken. Simultaneously, standard solutions of calcium carbonate with known concentrations (100, 200, 400, and 500 mg dm^{-3}) were prepared to establish a standard curve. The soluble calcium content in the sample was measured and expressed in mg per 100 g dry weight, taking into account the dry weight of the samples.

The parameters for the flame photometer used to read the calcium content are as follows:

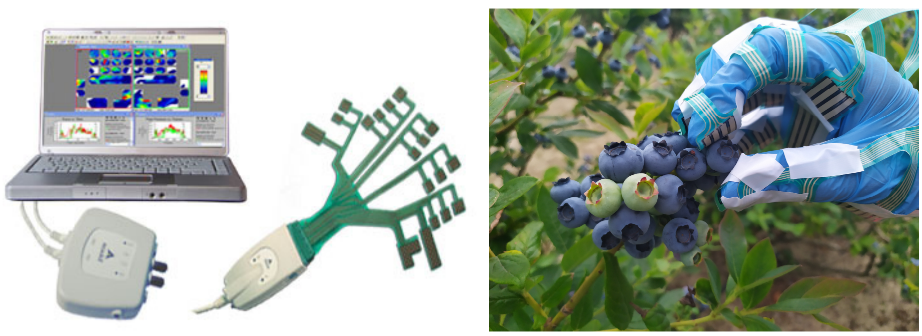
- Flame photometer FA, Carl Zeiss, Jena Model III;
- Air pressure: 30–40 kPa;
- Acetylene pressure: 80–90 mm water column;
- Flame height: approximately 100 mm;
- Height of the flame cone (on the eyepiece): approximately 30 mm;
- Nozzle diameter: 0.6 mm;
- Filter: Ca 63 J.

The samples from each measurement section comprised 15 fruits.

2.4. Picking Tests

Fruit picking tests were conducted on nine separate segments of the blueberry plantation (located in Szczodrów, Lower Silesia, Poland), eight of which were subjected to various spraying techniques and one comparative control group. Fresh fruits were harvested in June 2024, at a temperature of 26 ± 0.1 °C and a relative humidity of 55%.

Picking experiments involved measuring the actual surface pressure between the fingers of the collector's right hand and the fruit (Figure 3b). A pulling technique was used during harvesting. The tests were performed using Tekscan equipment (South Boston, MA, USA), which featured a key component—a flexible sensor (Grip Sensor model 4256E) (Figure 3a).



(**a**) (**b**)

Figure 3. Schematic diagram of the Grip System set-up (**a**) and a depiction of the pressure sensor on the collector's hand (**b**).

The sensor used had 18 active areas, a thickness of 0.1 mm, a sensor density of 6.2 sensors cm^{-2}, and a pressure range of 345 kPa. Data transmission to the computer was facilitated by a hub (VersaTek 2-Port Hub) connected to a cuff (VersaTek Cuff) in which the pressure sensor was placed. The system, together with the F-Scan Research 6.85 software, enabled real-time data recording with a sampling rate of up to 750 Hz.

Picking tests were conducted in three replicates for each study segment. Each individual measurement lasted 120 s, during which time, data were recorded for 30 to 35 fruits. Approximately 810 fruits were examined. The measurement system calculated the surface pressure values based on the recorded total load and contact area. Contour images for individual impulses were read only for the interacting fingertip at the maximum surface pressure value p_{maxp} and the corresponding force F_{pf} (picking force). Picking force represents the resistance that must be overcome to detach the blueberries from the stem and is, therefore, a function of the force that needs to be applied on the fruit using the fingertips.

2.5. Compression Tests

In the subsequent phase, the quality of the blueberries was assessed based on their mechanical and physical properties. Freshly harvested berries were transported, on the same day, to the Agrophysics Laboratory at the Institute of Agricultural Engineering, Wrocław University of Environmental and Life Sciences, where they were meticulously selected in terms of mass and geometry. Laboratory conditions were maintained at 27 ± 0.1 °C and 55% relative humidity. The mean equatorial diameter and height of each fruit were measured using an electronic calliper with an accuracy of 0.01 mm (Hogetex, Varsseveld, The Netherlands). The fruit mass was determined using an electronic balance (RADWAG WTC 200, Radom, Poland) with a weighing range of 200 g and an accuracy of 0.001 g. For the selected group of berries, the compressive firmness test was conducted using an Instron 5566 universal testing machine (Norwood, MA, USA), integrated with a Tekscan surface pressure system (South Boston, MA, USA) (Figure 4).

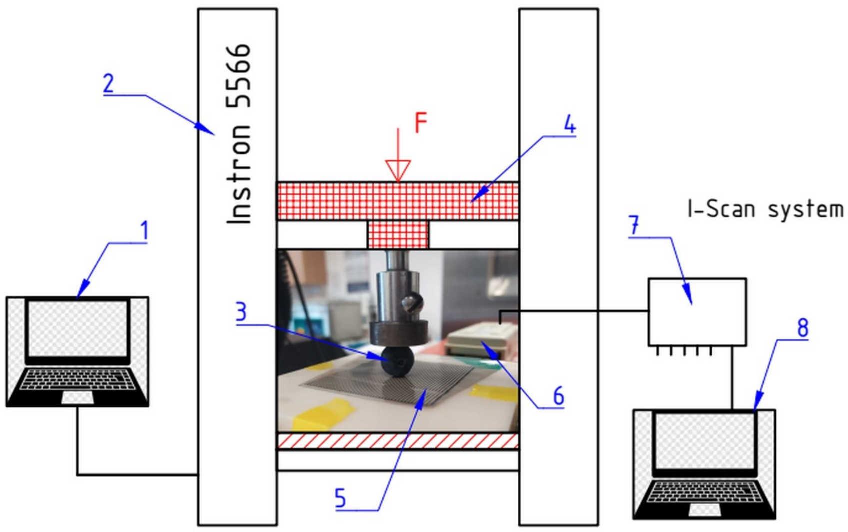


Figure 4. Scheme of equipment used in compression tests: 1—computer of testing machine with Bluehill 2 software; 2—Instron 5566 testing machine; 3—compressed fruit; 4—loading head; 5—foil pressure sensor; 6—VersaTek Handle; 7—multi-channel VersaTek Hub concentrator; 8—second computer supporting I-Scan system.

Each whole fruit was placed laterally on a foil pressure sensor (model 5051, range 344.7 kPa) affixed to a non-deformable base, and it was subjected to uniaxial compression between two parallel machine plates until rupture, at a loading speed of 0.00083 m s^{-1}. Compression tests up to fruit destruction illustrated the combined mechanical resistance of the skin and pulp tissue. Data transmission to a computer was facilitated by a multichannel hub (VersaTek 8 Port Hub) connected directly to the sensor handle (VersaTek Sensor Handles) in which the pressure sensor was placed. The I-Scan 7.6 software system enabled real-time data recording, with a sampling rate of up to 5 kHz. Based on the contour images, simultaneous readings of peak surface pressures and the corresponding values of load, deformation, and contact area were obtained. A total of 270 berries were used for the compression tests, and the experiments were conducted in thirty replicates for each of the nine groups.

2.6. Statistical Analysis

Basic statistical analyses (means, standard deviations (SD), standard errors (SE), medians, and quartiles Q1 and Q3) were carried out in Microsoft Excel. The conformity of groups to a normal distribution was assessed in STATISTICA 13 (TIBCO Software Inc., Palo Alto, CA, USA) using the Shapiro–Wilk test, and the homogeneity of variances was evaluated using Levene's test. ANOVA was conducted to test the significance of differences in strength parameters dependent on independent spray parameters. Post hoc comparisons between groups were performed using Tukey's HSD test. Pearson correlation coefficients were also calculated to assess the relationships between the mass and the geometric and mechanical parameters. A significance level of $p < 0.05$ was adopted, indicating statistically significant differences.

3. Results

3.1. Coverage Degree and Calcium Content

The results of the cumulative coverage rate of the sprayed surfaces, along with the standard deviation (SD) values, are presented in Figure 5. The lowest value of this parameter was observed in the plot where one-stream AIXR air induction nozzles were used, at a driving speed of 5.5 km h^{-1} and a pressure of 0.2 MPa. The highest coverage was achieved at a liquid pressure of 0.4 MPa and a driving speed of 2.5 km h^{-1}, during fertilisation with standard XR nozzles.

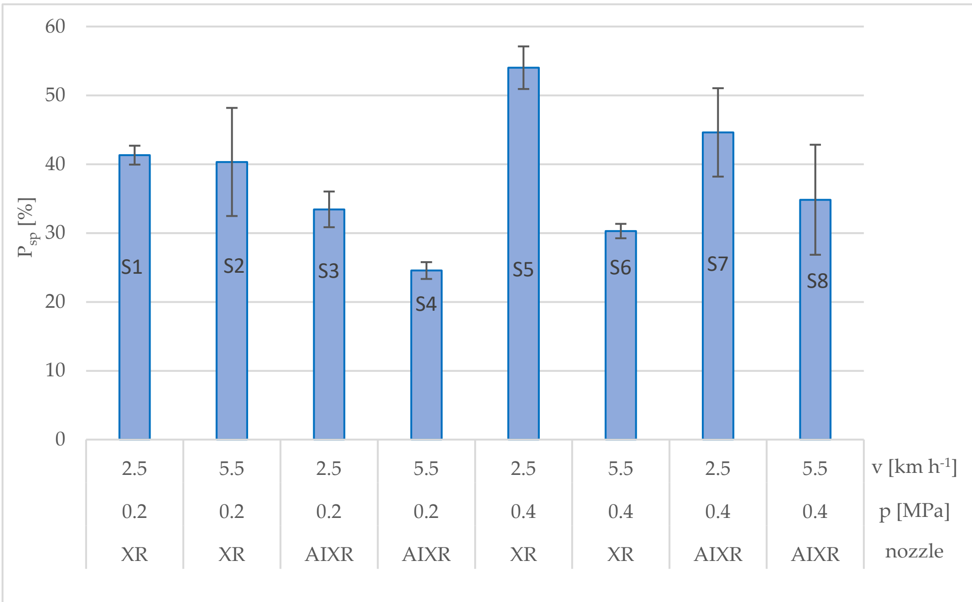


Figure 5. Cumulative coverage degree. Error bars indicate the mean ± SD. Spray parameters are denoted as follows: v2.5 and v5.5 (travel speeds of 2.5 and 5.5 km h^{-1}); p0.2 and p0.4 (working liquid pressures of 0.2 and 0.4 MPa); and the nozzle types XR and AIXR (standard and air induction nozzles).

The results of the calcium content measurements in the fruits are presented in Figure 6. The lowest calcium levels were observed in fruits collected from the plot where no fertilisation was applied. The highest calcium content was obtained during the treatment with a pressure of 0.4 MPa and a driving speed of 2.5 km h^{-1} for both types of tested nozzles. It is also notable that a higher calcium content in the fruits was achieved with an increased spray pressure.

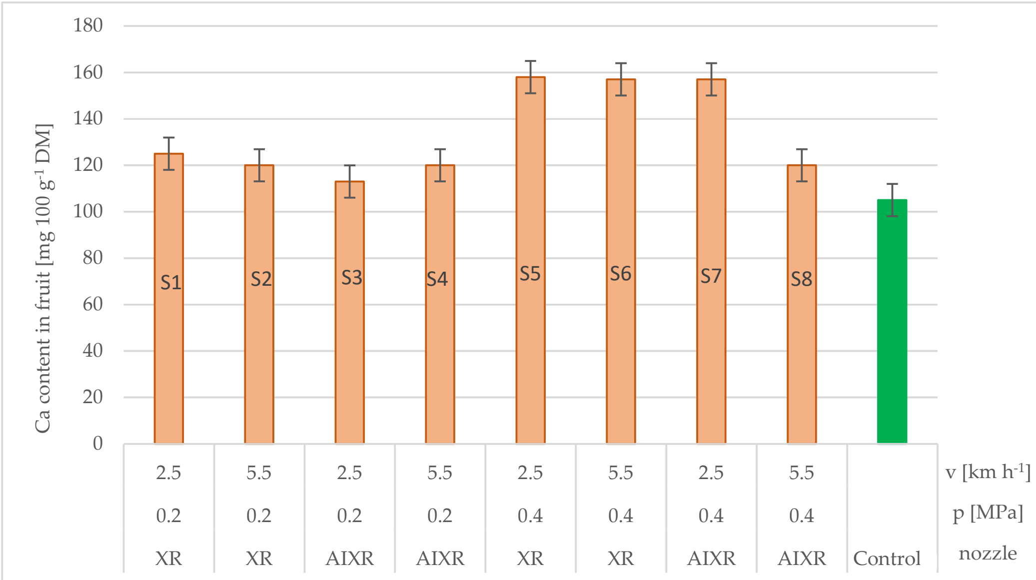


Figure 6. Calcium content in fruits. Error bars indicate the mean ± SD. Spray parameters are denoted as follows: v2.5 and v5.5 (travel speeds of 2.5 and 5.5 km h^{-1}); p0.2 and p0.4 (working liquid pressures of 0.2 and 0.4 MPa); and the nozzle types XR and AIXR (standard and air induction nozzles).

3.2. Test Material Properties and Picking Test Results

Table 1 presents the basic physical properties of the selected blueberries collected during the harvest period. The comparison revealed a significant effect of the calcium spray applied on the increase in fruit size ($p < 0.05$), particularly at a pressure of 0.2 MPa, and using the AIXR nozzle, as compared to the control group (no spray), where the Spray 4 (S4) treatment caused a 79% increase in fruit weight. It was observed that the lowest increase in parameters was recorded for a mass of 1.33 g, a diameter of 14.42 mm, and a height of 10.93 mm for the spray (S1), using the XR nozzle at a speed of 2.5 km h^{-1}. The control group exhibited the lowest values for the aforementioned parameters.

Table 1. Properties of the research material.

	Spray 1 p0.2_XR v2.5	**Spray 2 p0.2_XR v5.5**	**Spray 3 p0.2_AIXR v2.5**	**Spray 4 p0.2_AIXR v5.5**	**Spray 5 p0.4_XR v2.5**	**Spray 6 p0.4_XR v5.5**	**Spray 7 p0.4_AIXR v2.5**	**Spray 8 p0.4_AIXR v5.5**	**No Spray CONTROL**
Mass [g]									
Mean	1.33	1.51	1.55	1.92	1.38	1.37	1.38	1.49	1.08
SD	0.06	0.07	0.03	0.10	0.05	0.04	0.06	0.05	0.05
Diameter [mm]									
Mean	14.42	15.25	15.26	16.72	14.99	15.11	15.05	15.58	13.74
SD	0.30	0.37	0.24	0.38	0.28	0.34	0.32	0.29	0.38
Height [mm]									
Mean	10.93	11.28	11.36	12.37	11.32	11.33	11.38	11.87	10.79
SD	0.42	0.39	0.37	0.46	0.47	0.29	0.39	0.40	0.34

The parameters of mass, equatorial diameter, and height of the fruits are presented as the mean ± SD values. Spray parameters are denoted as follows: v2.5 and v5.5 (travel speeds of 2.5 and 5.5 km h^{-1}); p0.2 and p0.4 (working liquid pressures of 0.2 and 0.4 MPa); and the nozzle types XR and AIXR (standard and air induction nozzles). Each group (Spray 1–8 (S1–S8) and No spray) comprised 30 repetitions.

The recorded impulses allowed the determination of the rupture forces (F_{pf}) occurring at the maximum (peak) surface pressure (p_{maxp}) exerted by the fingers interacting with the blueberry fruit. Since the field studies were randomly conducted on bushes, the statistical analysis revealed that not all groups exhibited a normal distribution ($p < 0.05$), requiring the use of a non-parametric Kruskal–Wallis analysis of variance. The Kruskal–Wallis test confirmed that there is a statistically significant difference ($p < 0.05$) between the untreated control group and the sprayed groups S1–8 (Figure 7a,b). The highest values of rupture forces and surface pressures were observed for the sprayed groups S1 and S2, at median levels of 3.4 N and 49.8 kPa, respectively, while the lowest values were recorded for the control group (1.9 N and 38.1 kPa). The correlational analysis between the mass and the geometric and mechanical parameters indicated a strong positive relationship between the rupture force and peak pressures (r = 0.83). However, fruit size had no significant effect on the forces required to detach them from the stem.

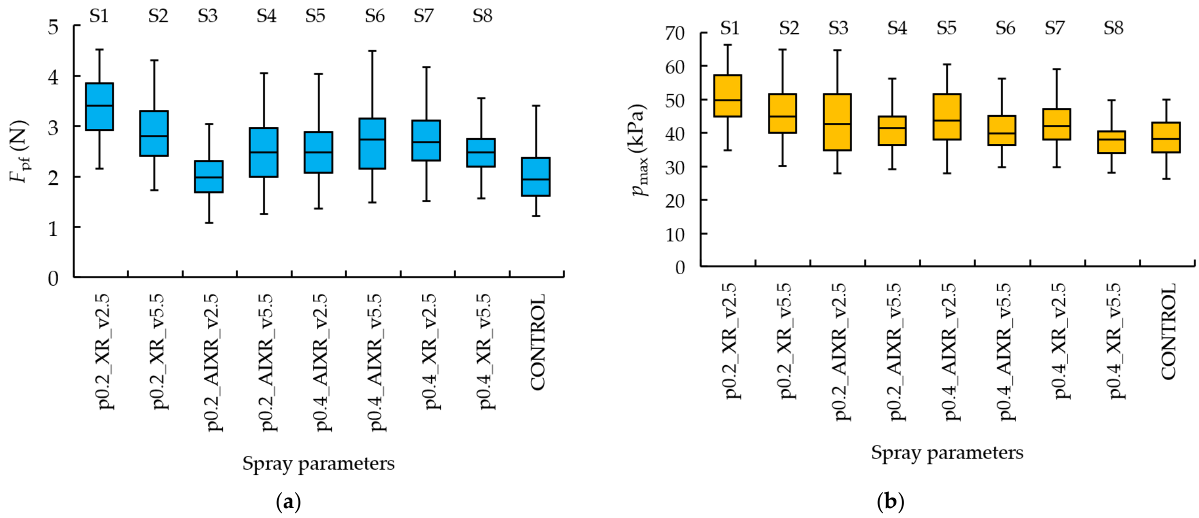


Figure 7. Changes in the recorded rupture forces (**a**) and the maximum surface pressures exerted by fingers (**b**) in relation to spray parameters. Spray parameter labels correspond to those in Table 1. Box plot notations: line—median; box—lower and upper quartiles Q1 and Q3; whiskers—minimum and maximum values.

Post hoc tests for multiple comparisons revealed that only groups S4, S6, and S8 showed statistically non-significant differences in terms of pressure. The highest contribution to the rupture pressure was observed to be generated by the index finger, followed by the thumb (Figure 8a). Example patterns of the force and peak pressure impulse during fruit detachment are shown in Figure 8b,c. The mean impulse (detachment) duration was 0.55 s.

3.3. Results of Compression Tests

Figure 9 shows the effect of spray parameters on the average changes in instantaneous destructive loads (F_c), which cause fruit damage in the compression tests. The selected material exhibited the consistency of the results within groups. The Shapiro–Wilk tests confirmed a normal distribution across all nine groups, and Levene's test verified the homogeneity of variance ($p > 0.05$). The ANOVA analysis clearly demonstrated the influence of spray variants on the maximum values of compressive force, as compared to the control group ($p < 0.05$). This finding was further confirmed by Tukey's post hoc tests, which showed statistically significant differences were observed in all eight groups relative to the control group. The greatest impact of the spray on destructive force variations was found in groups S3, S4, and S7, using AIXR air induction nozzles. These groups showed the highest resistance, at levels of 7.8–7.9 N. The control group recorded the lowest values, at 7 N. The correlation analysis also confirmed the association of destructive forces with mass and equatorial diameter (r = 0.59), which indicates that mechanical resistance also increases with an increase in blueberry size.

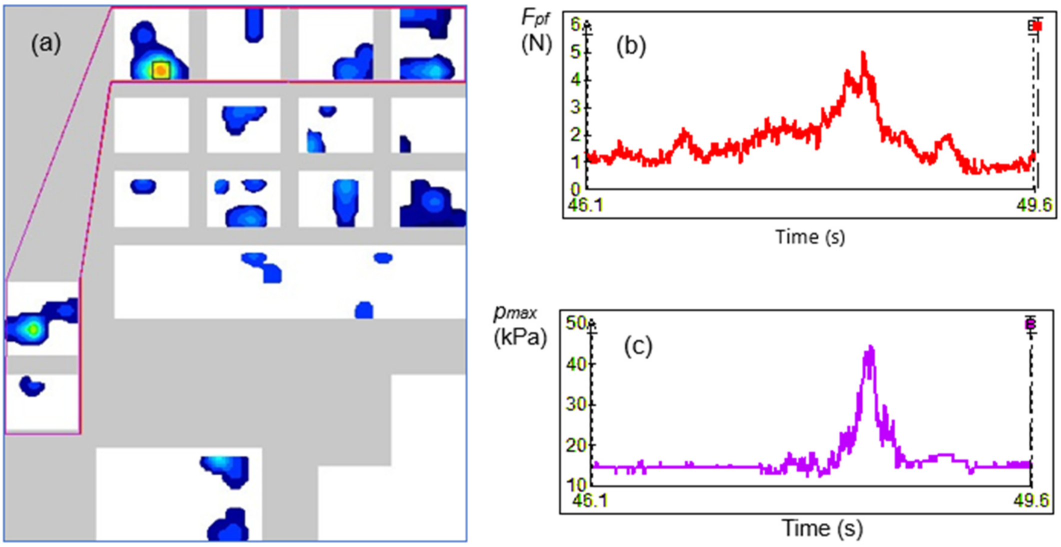


Figure 8. Contour view of surface pressures with the finger interaction area highlighted (**a**), along with the force and peak pressure impulses (**b**,**c**) recorded for a sample collection from group S1.

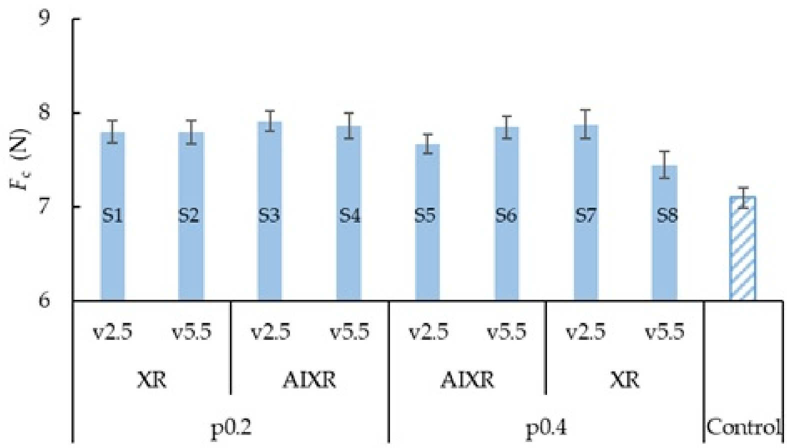


Figure 9. Comparison of maximum compressive forces in destructive tests for different spray variants. The spray parameter labels are as shown in Table 1. Error bars represent the mean ± SE.

Synchronisation of blueberry compression tests on the strength testing machine with the I-Scan surface pressure measurement system allowed for the simultaneous recording of compression forces, contact area, and peak pressures (Figure 10c–e). Pressure contour analysis revealed that, in the initial stage of compression, the maximum pressure zone is concentrated at a central point on the contact area (Figure 10a) and remains in this state until the peak value p_{maxp} is reached (Figure 10e). A further increase in the load causes the pressure peaks to shift towards the outer contact areas (Figure 10b), reaching a destructive peak pressure p_{maxc} and compressive force F_c, leading to the permanent rupture of the fruit skin.

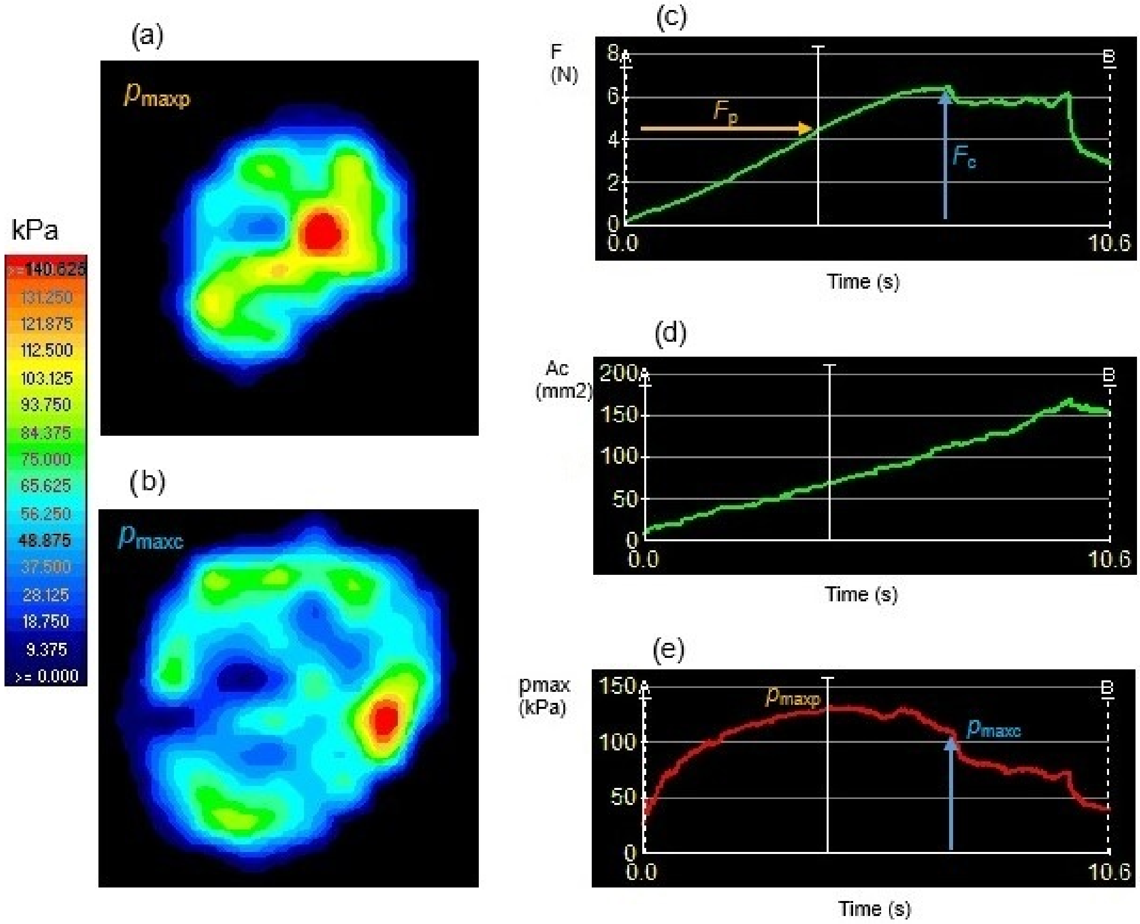


Figure 10. Example recording from the I-Scan system: (**a**,**b**)—contour maps of peak pressures for firmness force F_p and destructive force F_c; (**c**)—compressive force curve over time; (**d**)—contact area progression over time; (**e**)—peak pressure progression over time. The vertical white line at the peak surface pressure p_{maxp} allows us to determine the fruit firmness—the mechanical resistance force F_p—at the same time point.

The process showed that the maximum peak pressure p_{maxp} does not coincide in time with the maximum force F_c but occurs significantly earlier. This finding led the authors to conclude that the mechanical resistance (firmness) of the blueberry can be determined from the curve plots if the peak pressure p_{maxp} value is known, and the corresponding force F_p should be observed to derive it. It is suggested that the earlier occurrence of pressure peaks results from the elastic–plastic deformations and the anatomical structure of the fruit, specifically is tougher skin and softer pulp near the seed zones.

Figure 11 presents the effect of the spraying parameters on the average changes in the firmness values F_p and peak surface pressures p_{maxp} of fruits, determined on the basis of the contour image analysis from the I-Scan system.

The statistical analysis showed normal distribution and homogeneity of variance in all groups ($p > 0.05$). ANOVA confirmed the impact of the applied spraying techniques on changes in the firmness values and peak pressures compared to the control group ($p < 0.05$). Post hoc Tukey tests confirmed that blueberry firmness differed significantly from the control group in all eight sprayed groups, while peak pressures showed significant differences only in groups S4 and S8. The control group had the lowest firmness values, at 3.5 N. After calcium spraying, the greatest increase in firmness (40–45%) was observed in groups S3, S4, and S7, using AIXR and XR nozzles. These groups showed the highest mechanical resistance, equivalent to 4.9–5.2 N, corresponding to the peak pressures of 132.8–136.9 kPa.

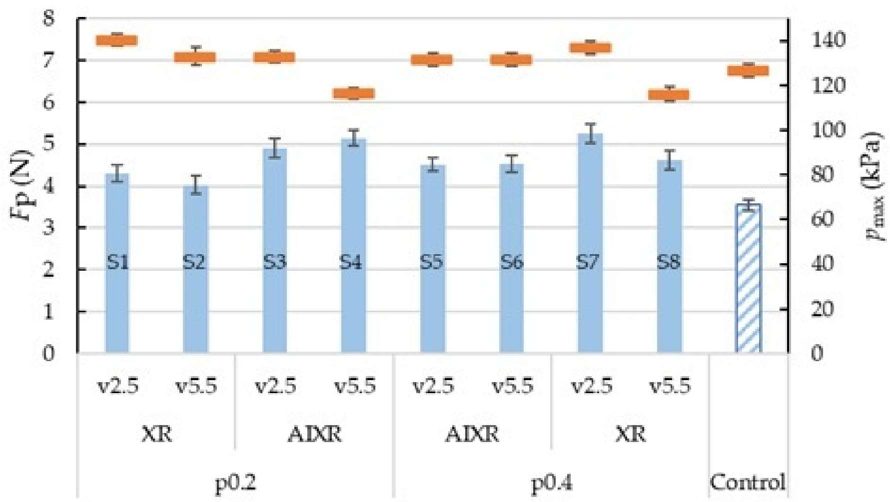


Figure 11. Changes in mechanical resistance (firmness) and peak surface pressures of fruit in relation to spray parameters. The spray parameter labels correspond to Table 1. Error bars represent the mean ± SE.

The peak pressure values varied irregularly from 140.6 kPa in group S1 to 116.3 kPa in S8. The reduction in peak pressure can be attributed to the increased fruit diameter, leading to a larger contact area. The correlation analysis revealed a strong association between fruit firmness and the mass and geometric parameters (r = 0.7); however, apart from groups S4 and S8, these factors had no effect on the peak surface pressure values.

Laboratory compression tests confirmed that the firmness F_p was about 79% higher than the detachment forces F_{pf}, with peak pressures increased by about 206%. This suggests that hand loads during manual harvesting are safe regarding mechanical damage. The obtained F_p forces notably correlated with the calcium content of the fruit and the degree of coverage by the applied solution, as presented in the previous subsection (Figures 7 and 8).

4. Discussion

The fertilisation process requires precision to ensure the effectiveness of treatments and minimise environmental impact. Research on the influence of fertilisation parameters on improving the mechanical properties of blueberries is highly relevant. Studies by Lobos et al. [25,38] have shown that calcium (Ca) sprays applied during fruit set and shortly thereafter enhance fruit firmness and reduce moisture loss. Additionally, the authors found that calcium sprays lead to higher calcium concentrations in the fruit, which correlates with increased firmness and better storage quality, aligning with the findings of our study.

The findings of Vance et al. [39] indicate that calcium treatments and application methods did not alter calcium concentration in leaves or fruit, nor did they affect fruit quality, firmness, or shelf life in any tested crop or variety compared to the control group. In contrast, Bryla et al. [40] reported that the foliar application of calcium chloride increased Ca content in the fruit but had a negative effect on yield and fruit quality. Sapkota et al. [41] reported findings based on field experiments conducted at wind speeds of 0.6–1.0 m·s^{-1}. Their study employed XRC standard nozzles alongside AIXR and TTI air induction nozzles, with variable driving speeds ranging from 2.7 m·s^{-1} to 6.25 m·s^{-1} at a pressure of 207 kPa. Their results demonstrated a decline in coverage rate with an increase in driving speed, consistent with our observations. Similarly, Ferguson et al. [42] observed higher coverage rates with XR nozzles compared to AIXR nozzles in experiments conducted on rye crops at a driving speed of 2.14 m·s^{-1} and a pressure of 207 kPa. Legleiter and Johnson [43] also achieved comparable coverage levels using both XR and AIXR nozzles. Furthermore, Ferguson et al. [44] showed that AIXR nozzles provided coverage levels comparable to those of the standard nozzles. Conversely, Creech et al. [45] found that XR nozzles provided the highest coverage in maize crops, while TTI nozzles were most effective for the application of crop protection products in soybean crops. These findings collectively underscore the necessity for further research into the influence of technical and technological factors, as well as atmospheric conditions during spraying, on treatment quality.

Firmness is a crucial indicator in assessing blueberry quality. Xu et al. [20] reported slightly lower firmness values than those obtained in this study, ranging from 2.7 to 3.3 N, using a different measurement approach for unsprayed fruit (texture analyser, probe diameter of 8 mm, and penetration speed of 3 mm s^{-1}). Calcium plays a significant role in fruit ripening and quality; regulates metabolism and physiological disorders; and maintains cellular structural integrity. Both the authors of this study and other researchers have observed that calcium content affects the maximum compression force (firmness) of blueberries in compression tests. This attribute was noted both immediately after the harvest and during the storage of the *Emerald* (firmer) and *Jewel* (softer) varieties [46,47]. Currently, there is a lack of critical data on blueberry strength studies regarding surface pressure measurements generated both during harvesting and in laboratory compression tests. Komarnicki and Kuta [48] investigated the impact of picking position on load changes and surface pressures exerted on fruit during manual harvesting, conducting their research on a strawberry plantation. The quality assessment studies of strawberries, conducted by Cieniawska et al. [22], showed that foliar calcium feeding significantly improved fruit quality in terms of both physical and mechanical properties; it increased fruit firmness (up to 66%), critical load levels (up to 36%), and maximum surface pressure values (up to 38%), without affecting the geometric parameters. The researchers confirmed that various spraying techniques have a positive impact on the mechanical resistance of fruit, with the key parameters determining the application effectiveness being the driving speed and spraying pressure.

Kuta et al. [37] presented a modern method for evaluating the strength properties of *Buenarosa* tomatoes, based on the direct measurement of finger pressure on the fruit surface using the Grip System. Their study showed that during red-stage picking, for all three body positions tested, the load and surface pressures exerted by the hand on the fruit did not exceed the critical compression thresholds (approximately 42–45 N and 138–146 kPa), which could cause tissue damage.

The study showed that the improvement in the mechanical properties of the fruits was largely due to the spraying technique used.

5. Conclusions

Applying calcium-based fertilisers can significantly enhance the firmness and post-harvest quality of highbush blueberries. However, the efficacy of such treatments depends on the type of calcium fertiliser used, the timing of application, and the specific blueberry variety. The optimisation of spraying techniques is essential for achieving the desired effects. Research indicates that foliar calcium spraying at a pressure of 0.2 MPa, combined with AIXR air induction nozzles, considerably improves fruit properties, increasing mass by up to 79%, geometric parameters by 21%, and fruit firmness by up to 45%. Furthermore, the results suggest that fruit size does not significantly influence the force required to detach it from the stem. The comparative analysis of the destructive compression and detachment tests confirmed that fruit firmness (F_p) is approximately 80% higher than the detachment force (F_{pf}), with peak pressures more than twice as high, suggesting that handpicking poses minimal risk for mechanical damage.

The study shows that understanding peak surface pressure contour maps is crucial in accurately determining the detachment load levels and firmness during compression. The innovative integration of destructive compression tests with surface pressure measurements effectively quantifies the mechanical resistance (firmness) of fruit. This methodology provides a valuable reference for detachment tests, enabling the assessment of the range of potentially damaging surface loads and pressures generated during hand harvesting.

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