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Research Paper

Bruising pattern of table olives (‘Manzanilla’ and ‘Hojiblanca’ cultivars) caused by hand-held machine harvesting methods

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ARTICLE INFO

Article history:
Received 24 May 2021
Received in revised form
7 January 2022
Accepted 12 January 2022
Published online 28 January 2022

Keywords:
Bruise index
Colour
Damage
Fruit characterisation
Mechanical harvesting
Olea europaea

This work presents a characterisation of the fruit and the bruising caused by some common detachment methods (manual, stick, shaker comb, branch shaker) and interception methods (net or padding) in common table olive varieties. We took pictures of fruit samples inside a special device, and the images were processed to extract characteristic parameters of shape and size (number of spots, Feret diameter, circularity, colours ...). Moreover, we studied the time evolution of bruising caused on the fruit by a controlled impact. Finally, we developed a system that allows synchronised rotation of the fruit with image capture to evaluate bruising on the whole volume of the fruit. Our results showed that different harvesting treatments produced differences in the average number and diameter of spots per fruit, as well as in the average area of the spots per fruit for the different varieties. Fruit colour or bruising can also serve as a control factor for computer vision characterisation, for which reason we recorded differences in the firmness of the bruised and non-bruised areas of fruit. The harvesting method that caused the highest median values of bruise index was the shaker comb, particularly for ‘Manzanilla’ with an index of 1.59% on padding compared to 0.24% for ‘Hojiblanca’. Net interception was also observed to increase the bruise index in ‘Manzanilla’ (5.85%). Bruising assessment that only considers a single photograph means that a considerable amount of bruising remains disregarded compared to the actual bruising on the whole volume of the fruit.

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https://doi.org/10.1016/j.biosystemseng.2022.01.010

1. Introduction

The cultivation of the olive tree (*Olea europaea* L.) enjoys sustained growth at a global level, currently reaching 10.5 Mha (FAO, 2019). Slightly less than half of the total production, 2.9 million tonnes, is destined for table olives. Spain plays a major role in the table olive sector, with a production of 0.5 million tonnes (IOC., 2020). The 'Manzanilla', 'Gordal' and 'Hojiblanca' cultivars (Campus, Degirmencioglu, & Comunian, 2018) are the most common commercial varieties due to their good pulp/pit ratio, and green processing is one of the most common methods employed for table olives. The Spanish style, which predominates in this method (Sánchez-Gómez, García-García, & Garrido-Fernández, 2013; Royal Decree 679/2016), means that any fruit defects require special attention as they influence quality and, therefore, the price fruit can attain on the market. Any spots on the fruit's surface will determine its category for commercialisation (Royal Decree 679/2016Royal Decree 679/2016). Such defects can be classified according to their origin (Riquelme, Barreiro, Ruiz-Altisent, & Valero, 2008), and bruising constitutes the characteristic type of damage produced during harvesting.

Mechanical harvesting considerably increases the level of damage to fresh fruit such as table olives (Hussein, Fawole, & Opara, 2020). The main objective of the manual harvesting conducted in most table olive orchards is to reduce damage to the fruit. This causes a considerable loss of profitability since manual harvesting methods compete with the highly mechanised systems employed in modern olive growing for the new intensified planting systems. Advances in this field are oriented towards comprehensive mechanisation using combined harvesting machinery (Ferguson et al., 2010; Sola-Guirado, Castillo-Ruiz, Blanco-Roldan, Gonzalez-Sanchez, & Castro-García, 2020) and post-harvest systems (Rejano, Montaño, Casado, Sánchez, & De Castro, 2010; Zipori, Fishman, Zelas, Subbotin, & Dag, 2021). In many farming contexts, mechanisation is not a valid solution due to the existing orography, the small size of the farm or a lack of resources, all of which make the introduction of machinery difficult. The only alternative on these farms is harvesting with semi-mechanised systems (Bernardi et al., 2018) such as branch shakers and shaker combs, or traditional methods like beating or hand picking, in which the fruit falls onto nets or suspended systems. These semi-mechanised harvesting systems detach the olive in a different way, so it seems logical to think they will also produce a different damage pattern. Similarly, since damage is related to the level of energy they receive (Jiménez-Jiménez, Castro-García, Blanco-Roldán, Agüera-Vega, & Gil-Ribes, 2012), there may be a relationship with the interception system, due to the correlation between damage and the height of the olive drop (Saracoglu, Ucer, & Ozarslan, 2011).

Opara and Pathare (2014) list different procedures to characterise damage in different fresh fruit. Non-destructive techniques such spectral imaging, nuclear techniques, thermal imaging and ultrasound imaging, among others, have a great potential to determine the internal properties of fruit and detect bruising (Stella et al., 2015; Mohammed Raju, Jannat, Wang-Hee, Changyeun, & Byoung-Kwan Cho; Du et al., 2020). Computer vision techniques are more limited in that they can only characterise external damage to fresh fruit. However, for the characterisation of green olives that will be processed Spanish style (Campus et al., 2018), visible spectral imaging may be sufficient to perform bruise characterisation with traditional, low-cost technologies. Surface damage means any defect in the exocarp of a fruit, and may be associated with damage to the innermost layers, so damage might be visible and measurable (Li & Thomas, 2014). It is difficult to establish empirical formula for the quantification of bruising, which depends on different parameters such as variety and maturity status among others. A proper characterisation should take into account the amount, shape and colour of the damage.

Bruise area is particularly suitable for the quantitative characterisation of damage. If the relationship between the bruise area and the overall fruit area is considered (Jiménez-Jiménez, Castro-García, Blanco-Roldán, González-Sánchez, & Gil-Ribes, 2013) it is possible to establish a bruise index (BI). This classification allows for a quantitative qualification of the damage, without establishing discrete levels, as proposed by Hadi, Ahmad, & Akande, 2009. It is important to take special care to quantify fruit bruising over the total surface area of the fruit. (Corkidi, Balderas-Ruíz, Taboada, Serrano-Carreón, & Galindo, 2006). The relationship of bruise index with the most commonly employed table olive harvesting systems would provide valuable information to improve the quality of mechanisation. Likewise, another parameter of interest could be the characterisation of the shape of damage in olives, in line with the considerations of other authors regarding bruise calculation in other fruits (Kitthawee, Pathaveerat, Srirungruang, & Slaughter, 2011; Mohammed et al., 2017; Van Zeebroeck et al., 2007). Image analysis can also determine the colour and ripeness of olives (Guzmán, Baeten, Pierna, & García-Mesa, 2015). Other studies (Beyaz, Martínez Gila, Gómez Ortega, & Gámez García, 2019) indicate the interest of applying similar methods to determine the colour of the type of fruit damage known as browning in the segmentation of olive damage. Bruising is changeable and requires the study of its evolution from its beginning (Jiménez-Jiménez, Castro-García, Blanco-Roldán, González-Sánchez, & Gil-Ribes, 2013).

To determine olive bruising quantitatively and qualitatively, visible imaging systems with computer techniques have shown great potential for delimiting the browned fruit areas after harvesting (Jiménez-Jiménez, Castro-García, Blanco-Roldán, González-Sánchez, & Gil-Ribes, 2013; Beyaz, Özkaya, & İçen, 2017; Ponce, Aquino, Millan, & Andujar, 2019). The aim of this article is to characterise the fruit and the bruise that occur in green table olives, specifically the 'Hojiblanca' and 'Manzanilla' varieties, employing computer vision techniques after the use of common harvesting methods. These parameters were evaluated when external damage had stabilised and, in addition, during temporal evolution. The comparison of damage quantification also took into account the entire surface of the fruit versus only one side of the fruit.

2. Materials and methods

We conducted a series of trials, which consisted of harvesting olives according to different treatments and analysing the pattern of external damage caused to the fruits by means of image analysis.

2.1. *Obtaining images to characterise the olives*

The olive samples were placed in 0.18 m square polylactic acid (PLA) trays, covered in blue foam with ellipsoid perforations for the placement of 20 fruits (Fig. 1). The samples were placed in a closed lighting device (Sola-Guirado, Bayano-Tejero, et al., 2020) with controlled lighting 13.95 $\pm$ 0.57 lux, and a colour temperature of 5500 K from 4 LED bars on the floor at 30°, with diffused lighting. A digital camera (Nikon, D80, Tokyo, Japan) was placed over of the samples, 570 mm above the tray surface, to take photographs at an aperture setting of f/6.3, shutter speed E:1/125 s, light sensitivity ISO:160, focal length FL: 35 mm, and exposure compensation EB:-1 EV. The resolution of each photograph was 3872 $\times$ 2592 pixels per tray area with a fruit resolution of 226 $\times$ 197 pixels.

Each photograph was digitally processed by an expert using ImageJ software (National Institute of Mental Health) to characterise the fruit and its bruised area. To do this, the picture was first cut to obtain 20 individual photographs of each fruit, identified according to its treatment. Segmentation converted each photograph into a binary image to extract the fruit measurements. Then, by adding the binary photo to the original fruit photo, the background was removed, leaving only the fruit. Finally, the bruised area of each fruit was manually segmented to obtain another photograph with the bruising areas. Analysis of the pictures reported the following useful parameters for characterising the fruit and bruising pattern:

- Fruit and bruise area (mm^2): the average number of pixels of each fruit or bruise scaled with its pixel-to-millimetre conversion.
- Bruise index (%), BI: ratio between the total bruise area of each fruit and its fruit area.
- Fruit length and diameter (mm). Largest and smallest distance between two points on the fruit area, usually coinciding with the major and minor diameters of the elliptical shape of the fruit.
- Maximum Feret diameter (mm) of the bruise spot: longest distance between any two points along the spot selection boundary.
- Circularity (#): the roundness or similarity to a perfect circle of the fruit or bruised spot, which varies from 0 to 1, with 0 corresponding to an infinitely elongated polygon and 1 to a perfect circle.
- Number of spots: number of bruised spots per fruit.
- Colour: coordinates on the average RGB colour space of the pixels of each fruit without taking into account the bruised area, or of the bruised spot itself.

2.2. *Harvesting treatments of trees and olive samples*

We conducted the trials on two different plots of 'Manzanilla' table olives and another two plots of 'Hojiblanca' destined for green processing, located in Cordoba (Spain) during the months of September and October of the 2018/19 and 2019/20 harvesting campaigns. The trees were under irrigation and without biotic or abiotic stress. The harvesting systems used to detach the fruit were those habitually employed for this purpose: manual picking (M) as a reference treatment, manual beating with a long fiberglass pole (B), semi-mechanised with a branch shaker (BS) (Stihl, SP 481, Waiblingen, Germany), and semi-mechanised with a shaker comb (SC) (Pellenc, P230, Pertuis, France). The vibration signals produced by the harvesting methods on the main branches were recorded using a MEMS triaxial accelerometer (Gulf Coast Data Concepts LLC X200-4, Waveland, MS), with a measurement range of $\pm$2000 m s^{-2}, a sensitivity of 0.06 m s^{-2} and a sampling frequency of 400 Hz. Table 1 summarises the vibration patterns that characterised these systems on the branches. Each tree was harvested from branches located between 1.5 and 2.4 m above the

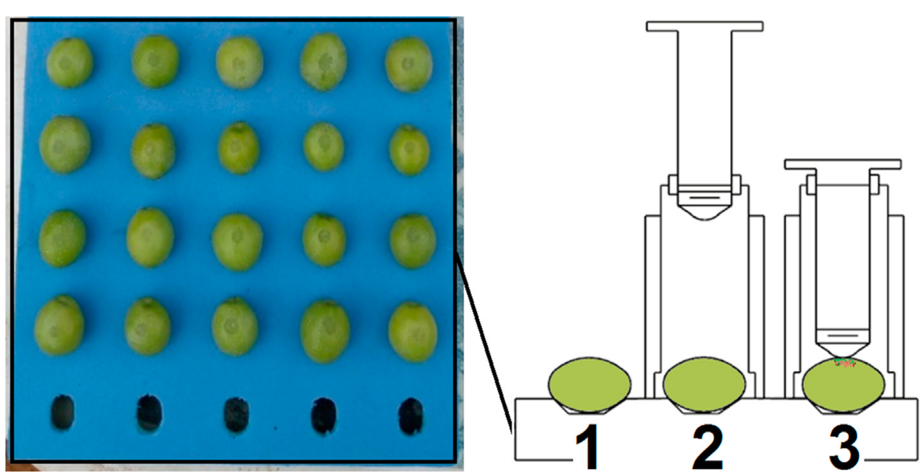

Fig. 1 – Tray with impacted fruit and sequence of impact caused by free-fall of the ball.

Table 1 – Vibration parameters of fruit-bearing branches with harvesting systems.

Harvesting method	Mean resultant acceleration ($m \cdot s^{-2}$)	Frequency (Hz)
Stick beating	560.7 ± 214.3[a]	–
Shaker Comb	79.6 ± 42.6	14.0 ± 0.4
Branch shaker	209.3 ± 81.1	20.6 ± 1.1

Values showed are mean ± standard deviation.
[a] Mean peak value.

ground by a farm worker, using the usual technique employed on the plot. An agricultural textile netting (N), as usually used in olive harvesting, was placed on the floor, along with a padding surface (P), consisting of two layers of 3 mm thick polyvinyl chloride filled with air with a diameter of 1 m at a height of 0.1 m. Olive samples were taken from the padding to study the exclusive incidence of the detachment method. In the case of the 'Manzanilla', variety, which has greater susceptibility to bruising (Jiménez-Jiménez, Castro-García, Blanco-Roldán, González-Sánchez, & Gil-Ribes, 2013), samples were also taken from the net in areas far from the padding to study the incidence of the interception means on this variety. In addition, randomly hand-collected samples without external damage were harvested and an impact or hit (H) was applied to the centre of the fruit. To perform the impact, a device was used in free fall from a height of 0.125 m with a steel ball that had a mass of 0.035 kg, applying an energy of 0.043 J (Fig. 1).

The following treatments were thereby obtained: M–P, BS-P, SC-P, B–P for 'Hojiblanca' and M–N, M–P, BS-N, BS-P, SC-N, SC-P, B–N, B–P for 'Manzanilla' and H for both varieties. The samples obtained in each of the treatments, were kept dry at an average temperature of 23 °C and photographed 150 min after harvesting, when the bruise had stabilised (Jiménez-Jiménez, Castro-García, Blanco-Roldán, González-Sánchez, & Gil-Ribes, 2013)., avoiding those that circumscribe the perimeter of the plot. Three rows of trees were randomly selected and, in each row, three trees were again randomly selected to apply the treatments (1 tree exclusively used for 1 harvesting method). When selecting rows, those corresponding to the perimeter of the plot were discarded, as were the trees at the beginning and end of the row. Twenty fruit samples (1 tray) were taken from each tree for each treatment (BS–P, SC-P, B–P, BS-N, SC-N, B–N), resulting in a total 60 samples per treatment and day. Treatments with a common harvesting method were applied on the same tree, and samples were harvested simultaneously using the net or padding surface. For the reference treatment (M), olives were randomly harvested from the 3 trees in the row before application of the treatments. In case of impact treatment (H), I olive samples were also collected from the 3 trees for the treatments in the row, on different areas of the tree and without previous bruising. These trials were repeated 4 times per campaign and plot, spaced approximately 5 days apart, leaving a minimum difference of 4 days in the event of rainfall.

2.3. *Characterisation of olives and their external damage*

We conducted different types of studies to determine useful parameters for modelling olives and their bruising:

1. Size and shape characterisation: Several geometrical parameters were taken for the fruit (length, diameter, and circularity), for the bruised spots they had (number of spots, Feret diameter and circularity) and for all treatments, extracting the information from image analysis. In addition, the fruit mass (g) was measured with a digital scale (Gram, EH-500, Spain).
2. Firmness assessment: The penetration force needed to break the fruit surface was measured with a penetrometer using a cylindrical 3 mm long and 2.4 mm diameter tip (IMADA Inc., DS2-11, USA) in non-bruised and bruised areas (the latter from spot areas greater than 16 mm^2).
3. Colour determination: The colorimetric characteristics of the olive in fruit areas with damage (spot area greater than 16 mm^2) and without damage were measured for all treatments using a colorimeter (Konica Minolta, CR-400, USA) calibrated with a D65 2° illumination measured in CIELAB colour space. Similarly, we determined the RGB colour coordinates of the images processed.
4. Bruise index and its time evolution: The bruise index was determined 150 min after harvesting for all treatments, using image analysis to extract the fruit area and damage area. Moreover, images of the fruit impacted with the free-fall device (H) were taken every 15 min up to 150 min, to evaluate the development of bruising over time.
5. Location of the bruising on the surface of the fruit: Calculation of the bruise index normally uses a single image, ignoring what occurs in the unseen areas, considering the ellipsoid geometry of the olives. To evaluate fruit bruising considering the entire surface of the fruit, we designed a prototype (Fig. 2) to rotate the olives on their main axis. The device consists of several gears, with two needles in their centres, where randomly selected fruit samples are placed. We evaluated 60 fruit samples per harvesting treatment and variety, 150 min after their harvest. A motor (4076 steps per turn) controlled by a microcontroller (Arduino, Nano, Italy) rotated the fruit, shifting 15° at a time to take 24 pictures per fruit in each position of the revolution.

To determine the amount and location of the bruising produced over the whole surface, the pictures were processed to give a complete two-dimensional representation of the olive without deformation (Fig. 3):

a. Each of the captured images was cropped to avoid overlapping of the same area, circumscribing an ellipse whose major diameter coincided with the fruit length

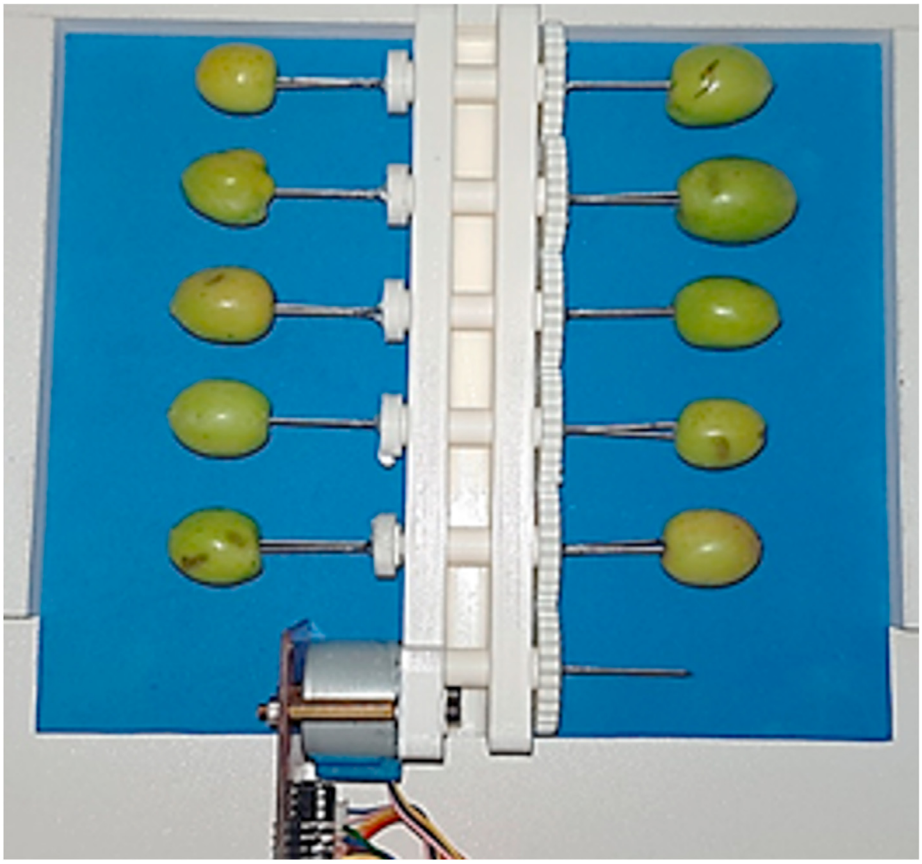

Fig. 2 – Device developed for turning olives and taking images from different sides.

and whose minor diameter is the fruit perimeter ($\pi \cdot$diameter) divided by 24.

b. Each cut was joined to the consecutive one.
c. All pixels of the composition are grouped together to give continuity to the composition while maintaining the equatorial line constant.
d. The remaining composition was enlarged by projection onto the curvature of the ellipse in the front view, i.e. by making the distance between the peduncle and its antipode coincide with half the perimeter of the ellipse determined in the front view.

In all cases, we investigated the relationship that exists for all of the studied variables with both the harvesting method and the interception method (in the case of 'Manzanilla'). We also analysed the differences between the different varieties before finally studying relationships existing within the different study parameters.

3. Results

3.1. *Fruit and fruit bruising size and shape characterisation*

Table 2 shows the characterisation of shape and size of the fruits sampled for the two harvesting seasons according to the different methods. Fruit mass, length and diameter variables showed a normal distribution (Kolmogorov–Smirnov, $p > 0.05$) for both varieties. A comparison of the harvesting methods (ANOVA test, $p > 0.05$; post-hoc Tukey test, $p > 0.05$) showed no significant differences in the variables of mass, length and diameter for the two varieties and seasons, nor did we find any significant differences between the net and padding catching systems (ANOVA test, $p > 0.05$; post-hoc Tukey test, $p > 0.05$). However, we did find significant differences (Student's t-test, $p < 0.05$) within each variety in the comparison of the 2019 and 2020 seasons: The diameter and length of fruit for both varieties showed a strong positive correlation with fruit mass ('Hojiblanca': Pearson Coefficient = 0.88; Pearson Coefficient = 0.89; $p < 0.05$; 'Manzanilla': Pearson Coefficient = 0.88; Pearson Coefficient = 0.91; $p < 0.05$). Circularity did not show a normal distribution (Kolmogorov–Smirnov, $p < 0.05$). Significant differences were found in circularity between varieties (Wilcoxon–Mann–Whitney Test, $p < 0.05$), with a median value and interquartile range in 'Hojiblanca' of 0.865 (0.023) and 0.869 (0.026) in 'Manzanilla', with diffuse differences between harvesting methods.

Table 3 shows some representative parameters of the characteristic size and shape of the fruit bruising spots. The number of spots per fruit did not follow a normal distribution. For both seasons and varieties, the number of spots was significantly different (Kruskal–Wallis, $p < 0.05$) between the manual method and the other detachment methods (post-hoc Wilcoxon rank sum test with Holm adjustment, $p < 0.05$), in which there were no differences between them (post-hoc

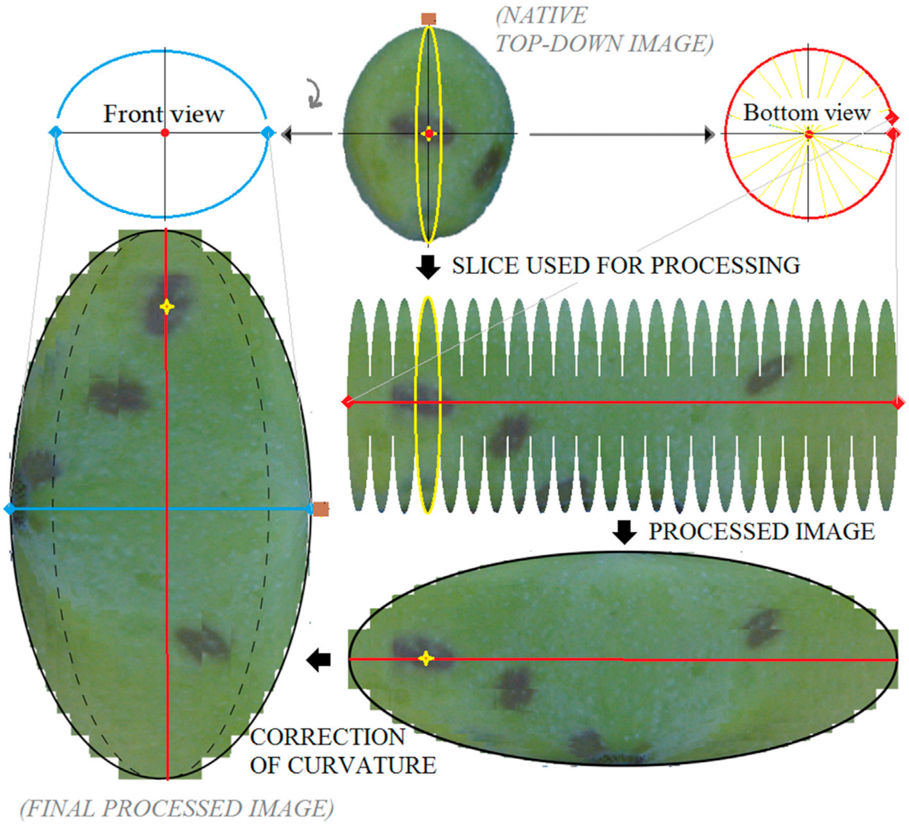

Fig. 3 – Process performed for the representation of the entire surface of an olive from the 24 photos of a fruit rotated 15°.

Table 2 – Fruit size and shape values measured in two harvesting seasons according to detachment method with padded catching and olive variety.

Detachment method	Variety	Mass (g)[a]	Length[a]	Diameter[a]	Circularity[b]
Manual	'Hojiblanca'	3.64 ± 0.84 a	22.42 ± 2.01 a	17.71 ± 1.49 a	0.869 (0.024) a
	'Manzanilla'	4.22 ± 1.00 b	22.72 ± 2.27 abc	18.62 ± 1.86 b	0.877 (0.024) b
Branch shaker	'Hojiblanca'	3.58 ± 0.83 a	22.43 ± 2.02 a	17.60 ± 1.56 a	0.864 (0.021) c
	'Manzanilla'	3.91 ± 0.98 c	22.92 ± 2.11 bd	18.47 ± 1.63 b	0.866 (0.026) ac
Shaker comb	'Hojiblanca'	3.56 ± 0.70 a	22.36 ± 1.64 a	17.68 ± 1.35 a	0.863 (0.024) c
	'Manzanilla'	3.90 ± 0.97 c	22.59 ± 2.13 ab	18.25 ± 1.78 b	0.867 (0.025) a
Stick beating	'Hojiblanca'	4.78 ± 0.86 d	23.32 ± 1.83 d	19.38 ± 1.41 c	0.878 (0.021) b
	'Manzanilla'	4.74 ± 0.79 d	23.16 ± 1.62 cd	19.35 ± 1.34 c	0.879 (0.022) b

Values shown are mean ± standard deviation or the median and the interquartile range in brackets. Different letters between rows of the same column indicate significant differences according to.
[a] Normal distribution (ANOVA, $p < 0.05$; post hoc pairwise t with pooled standard deviation and Holm adjustment method, $p < 0.05$) or.
[b] Non-normal distribution (Kruskal–Wallis, $p < 0.05$; post hoc Wilcoxon rank sum test with Holm adjustment method, $p < 0.05$).

Wilcoxon rank sum test with Holm adjustment, $p > 0.05$). In all cases, the number of spots within the same detachment methods increased in the net catching compared to padding catching. The circularity of spots was significantly different between detachment methods for 'Manzanilla' and 'Hojiblanca' (Kruskal–Wallis, $p < 0.05$; post-hoc Wilcoxon rank sum test with Holm adjustment, $p < 0.05$), and was lower for the latter in all cases. The mean greater Feret diameter of the spot was different (Kruskal–Wallis, $p < 0.05$; post-hoc Wilcoxon rank sum test with Holm adjustment, $p < 0.05$) between varieties and detachment methods, and slightly greater in 'Hojiblanca', except for the shaker comb, where they were the same.

3.2. *Firmness assessment*

Penetration force values in the bruised and non-bruised fruit zones followed a normal distribution (Kolmogorov–Smirnov, $p > 0.05$) for both varieties. Significant differences (Student's t-test, $p < 0.05$) were found between the bruised and non-bruised fruit zones in both varieties, with a value of 14.02 ± 1.92 N and 10.26 ± 1.73 N for the bruised zone in 'Hojiblanca' and 'Manzanilla', respectively, and a value of 17.11 ± 1.73 N and 13.02 ± 1.32 N for the non-bruised zones, in "Hojiblanca' and 'Manzanilla', respectively. Within each variety there were also significant differences between the

Table 3 – Fruit bruised spot size and shape values measured in two harvesting seasons according to harvesting method and olive variety.

Detachment method	Catching method	Variety	Number of spots	Feret Diameter (mm)	Circularity
Manual	Padded	'Hojiblanca'	0 (1) a	2.35 (2.10) a	0.709 (0.235) ab
	Padded	'Manzanilla'	0 (1) a	1.62 (2.20) b	0.788 (0.314) c
	Net		2 (3) b	2.21 (2.01) ab	0.674 (0.233) ab
Branch shaker	Padded	'Hojiblanca'	1 (2) c	1.53 (1.10) b	0.725 (0.205) a
	Padded	'Manzanilla'	2 (5) b	1.34 (0.83) c	0.787 (0.191) c
	Net		3 (4) d	1.99 (1.42) b	0.704 (0.198) ab
Shaker comb	Padded	'Hojiblanca'	1 (2) c	3.04 (2.60) d	0.628 (0.211) d
	Padded	'Manzanilla'	2 (3) b	2.79 (2.16) ad	0.677 (0.201) b
	Net		3 (2) d	4.41 (2.37) e	0.580 (0.162) e
Stick beating	Padded	'Hojiblanca'	0 (2) ac	2.08 (2.61) ab	0.666 (0.379) abd
	Padded	'Manzanilla'	0 (3) ac	2.37 (2.18) abd	0.664 (0.328) abd
	Net		2 (3) b	2.28 (2.34) abd	0.628 (0.305) abd

The values represented are median and interquartile range. Different letters indicate significant differences between rows of the same column (Kruskal–Wallis, $p < 0.05$; post-hoc Wilcoxon rank sum test with Holm adjustment method, $p < 0.05$).

bruised and non-bruised zones (paired t-test, $p < 0.05$), with an average reduction in penetration force of 18% for 'Hojiblanca' and 21% for "Manzanilla'.

In terms of harvesting methods, the fruits of both varieties followed the same trend in the non-bruised zones. There were significant differences of penetration force between the manual method, which had the highest value, and the other harvesting methods (ANOVA test, $p < 0.05$; post-hoc Tukey test, $p < 0.05$). In the non-bruised zone, no differences were found between the branch shaker and shaker comb for 'Hojiblanca' (Student's t-test, $p > 0.05$), with values of 14.91 ± 1.68 N and 14.10 ± 1.94 N, respectively, whereas differences were found between these methods for "Manzanilla' (Student's t-test, $p < 0.05$), with values of 11.82 ± 1.05 N and 9.73 ± 1.61 N. A positive correlation of fruit penetration force with fruit weight (Pearson coefficient $p < 0.05$) was found for both varieties in manual harvesting methods, considering that the fruit measured are destined for green processing.

Penetration force values in the non-impacted zone of the fruit showed variability over time. Significant differences were found in both varieties between the first four weeks and the fifth and sixth weeks (ANOVA, post-hoc Tukey $p < 0.05$; Kruskall-Wallis, post-hoc Wilcoxon–Mann–Whitney Test $p < 0.05$). We observed that the proportion of fruits with a higher maturity (higher Jaen index), increases as weeks go by (data not shown). In addition, the value of their penetration force was different among fruits, except for those with indices of 0 and 1 (ANOVA, post-hoc Tukey $p < 0.05$; Kruskall-Wallis, post-hoc Wilcoxon–Mann–Whitney Test $p < 0.05$), which decreased in value as the maturity index increased.

3.3. *Fruit and fruit bruising colour characterisation*

Table 4 shows the components of CIELAB colour space measured with the colorimeter on the fruit samples tested. The values of the 'a' component showed no differences between the different campaigns for each variety (Wilcoxon–Mann–Whitney Test, $p > 0.05$), unlike the 'L' and 'b' components, which were different for each variety (Wilcoxon–Mann–Whitney Test, $p < 0.05$). In addition, we observed no significant differences between the different mechanised harvesting methods or between the padding or net interception methods. The values of all components were higher in 'Manzanilla' than in 'Hojiblanca' in both seasons. In both varieties, negative relationships were measured between the 'a' and 'b' component of the CIELAB colour space (Spearman rho, $p < 0.05$) with significant relationships related to fruit mass and diameters (Pearson coefficient, $p < 0.05$; Spearman rho, $p < 0.05$) for 'Manzanilla'. Although this study only evaluated green fruits, when considering different maturity indices, the analysis of the fruit colour in RGB space extracted from the photographs shows a trend of colour evolution from deep green to black. (Fig. 4). Fruit colour over the six different weeks studied was significantly different (Kruskall-Wallis, $p < 0.05$) for each of the channels (RGB), with different red and green channel values for each week (post-hoc Wilcoxon–Mann–Whitney Test with Holm correction, $p < 0.05$).

3.4. *Bruise index characterisation*

- Bruise index 150 min after harvesting

The bruise index did not follow a normal distribution (Kolmogorov–Smirnov, $p < 0.05$). Figure 5 shows the median values obtained for the two varieties and the harvesting treatment studied. There were significant differences (Wilcoxon–Mann–Whitney Test, $p < 0.05$) for the two seasons between 'Hojiblanca' and 'Manzanilla' with greater damage suffered by 'Manzanilla'. Considering exclusively detachment method, i.e. comparing padding treatments, there were no significant differences between varieties using the manual method and manual beating with stick (Kruskal–Wallis, $p < 0.05$; post-hoc Wilcoxon rank sum test with Holm adjustment, $p < 0.05$). However, significant differences were found between varieties using the branch shaker (BI = 0.03 for 'Hojiblanca' and BI = 0.33 for 'Manzanilla') or the shaker comb (BI = 0.24 for 'Hojiblanca' and BI = 1.59 for 'Manzanilla'), with significant differences between both methods for the same variety (post-hoc Wilcoxon rank sum test with Holm adjustment, $p < 0.05$). Regarding the intercept method, i.e., comparing the same detachment method between padding and net, we found differences for all systems, which were

Table 4 – CIELAB colour space measured with the colorimeter on fruit samples impacted with the controlled energy method (H) and those harvested with the shaker comb, branch shaker and beating methods using padding in the interception.

Detachment method	Variety	L	A	b
Controlled energy (H) (damage zone)	'Hojiblanca'	52.9 ± 2.9 c	−15.1 ± 1.7 b	32.4 ± 3.2 c
	'Manzanilla'	52.6 ± 3.8 c	−11.5 ± 2.9 c	30.3 ± 3.8 d
Controlled energy (H) (undamaged zone)	'Hojiblanca'	58.6 ± 3.0 a	−19.2 ± 1.1 a	38.6 ± 2.3 a
	'Manzanilla'	62.1 ± 2.5 b	−18.8 ± 3.2 a	40.8 ± 3.5 b
Manual	'Hojiblanca'	59.5 ± 3.0 a	−18.6 ± 2.6 ad	37.8 ± 2.8 a
	'Manzanilla'	62.4 ± 2.3 b	−18.5 ± 2.0 d	39.4 ± 3.0 e
Mechanical harvesting (SC, BS, B)	'Hojiblanca'	59.0 ± 3.1 a	−19.0 ± 1.3 a	36.5 ± 4.6 f
	'Manzanilla'	61.9 ± 4.5 b	−18.3 ± 4.0 d	38.4 ± 2.9 a

Values shown are mean ± standard deviation. Different letter indicates significant differences between rows of the same column (Kruskal–Wallis, $p < 0.05$; post-hoc Wilcoxon rank sum test with Holm adjustment method, $p < 0.05$).
* The colorimeter was placed on a random area of the fruit regardless of whether the area was damaged or not, except for the controlled energy method, in which it was positioned just above the area impacted by the ball.

Fig. 4 – Colour evolution (R) during table olive ripeness throughout the harvesting season (median of the values in RGB space for Hojiblanca y Manzanilla). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

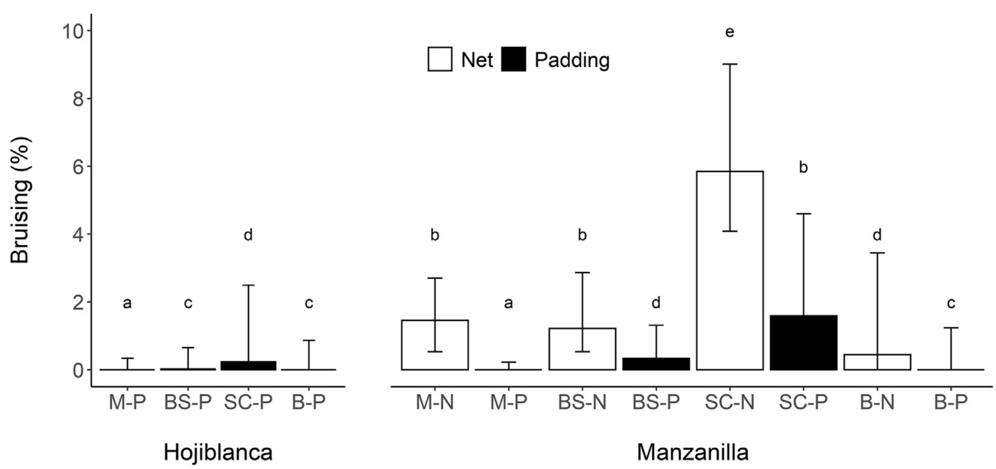

Fig. 5 – Bruise index for each treatment of fruit detachment (M: manual by hand, BS: branch shaker, SC: shaker comb, B: manual beating) and interception (N: nets, P: padding) and for each olive variety. The values shown represent median and interquartile range (Kruskal–Wallis, $p < 0.05$; post-hoc Wilcoxon rank sum test with Holm adjustment method, $p < 0.05$).

significantly higher with a net intercept (Kruskal–Wallis, $p < 0.05$; post-hoc Wilcoxon rank sum test with Holm adjustment, $p < 0.05$). The highest values were found using the shaker comb for both seasons and varieties with greater values in 'Manzanilla' (BI = 1.59 for padding and BI = 5.85 for net).

It is possible to make a nominal classification by placing bruise index limits (BI = 0, 0< BI < 1, 1< BI < 3, 3< BI < 5, BI > 5) in order to compare the level of damage studied by other authors (Castro-Garcia, Castillo-Ruiz, Jimenez–Jimenez, Gil-Ribes, & Blanco-Roldan, 2015: no damage, slight damage, moderate damage, severe damage, mutilated). However, this is only a proposal of thresholds since these authors used a visual classification so did not quantify the area of bruising used to define the limits. Figure 6 shows the distribution of bruising in the sampled fruit with our proposed classification. With the thresholds, we obtained a distribution of the level of damage caused by each harvesting method studied (Fig. 7).

- Bruise index and its development over time

Figure 8 shows the temporal evolution of the bruise index from the time the controlled method (H) impacted the olive. Bruise index values at different times post impact showed significant differences (Student's t-test, $p < 0.05$; Wilcoxon–Mann–Whitney Test, $p < 0.05$) between varieties. The median bruise index values were fitted to a logarithmic

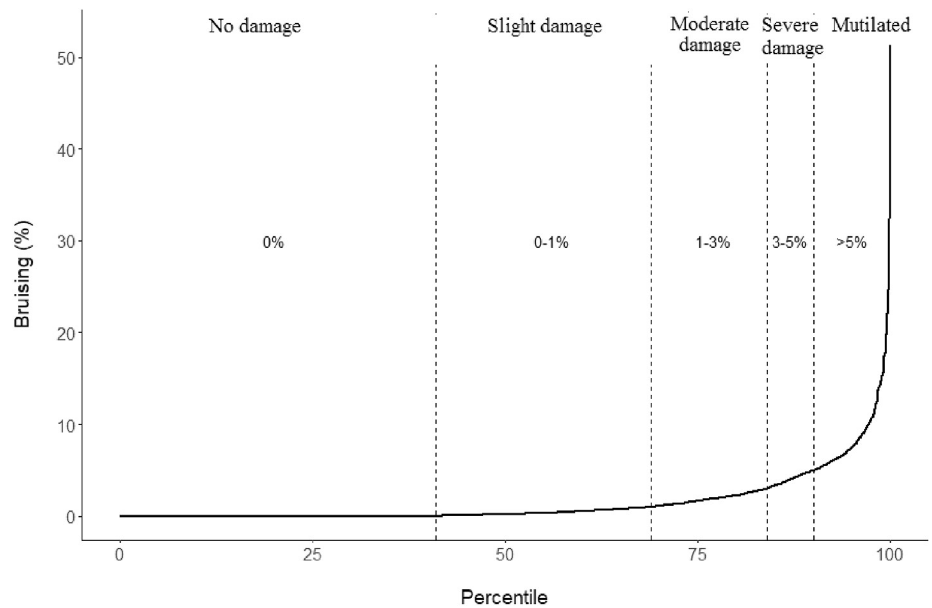

Fig. 6 – Distribution of bruising values, boundary lines of each damage category shown with vertical dotted lines.

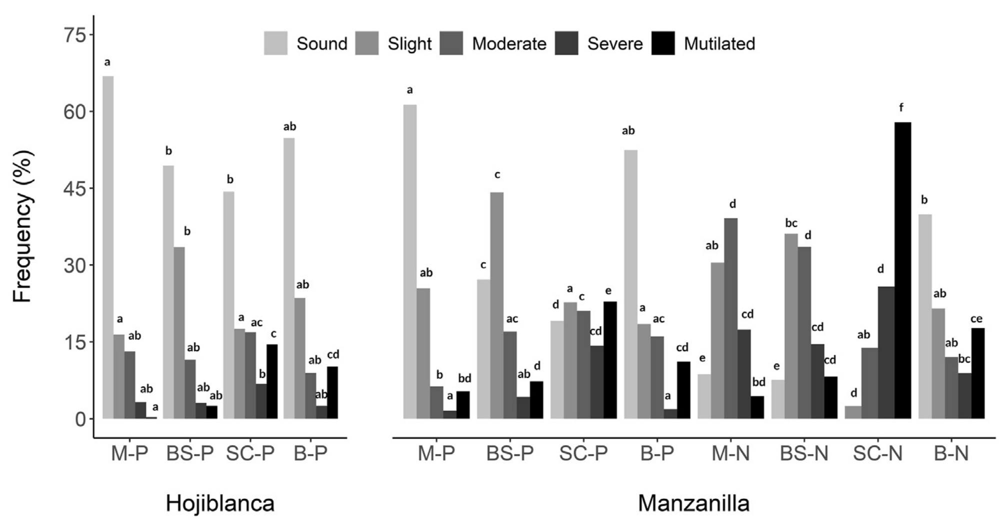

Fig. 7 – Frequency of damage category for each treatment of fruit detachment (M: manual by hand, BS: branch shaker, SC: shaker comb, B: manual beating) and interception (N: nets, P: padding) and for each olive variety. Different letter indicates significant differences between treatments in the same damage category (pairwise two-samples Z-test of proportions with Holm adjustment method, $p < 0.05$).

function in relation to the time post impact. Figure 9 illustrates the colour differences of the bruised spots between the RGB colour channels over time. Colour differences between the two varieties of fruit over the time were found in the red and green channel (Friedman Test $p < 0.05$) but not in the blue channel. The greatest changes over time occurred in the green channel, where values decreased with a greater slope in 'Manzanilla'.

- Location of the bruising on the surface of the fruit

Figure 10 shows the differences in the bruise index between analysing a single image that partially captures the surface of the fruit, and the proposed system, which captures the entire fruit surface. The methods based on branch shakers and manual harvesting showed significant differences between the bruise index determined from a single photo or from the whole perspective in true magnitude. Conversely, harvesting methods with shaker comb and beating showed no significant differences. In general, when the image of the spread external surface of the fruit is considered, there is a marked increase in the percentage of bruising, a median 140%, considering that 100% is the estimated bruising from a single unprocessed zenithal picture, although a high deviation exists in some cases.

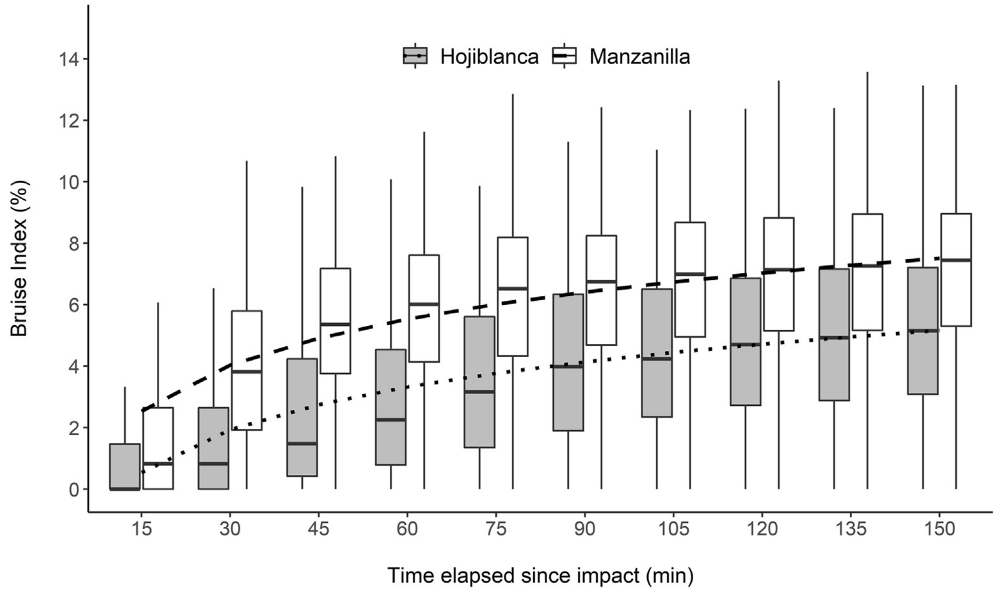

Fig. 8 – Temporal evolution of bruising colour in RGB colour space post impact for 'Hojiblanca' (grey) and 'Manzanilla' (white) varieties measured from the images.

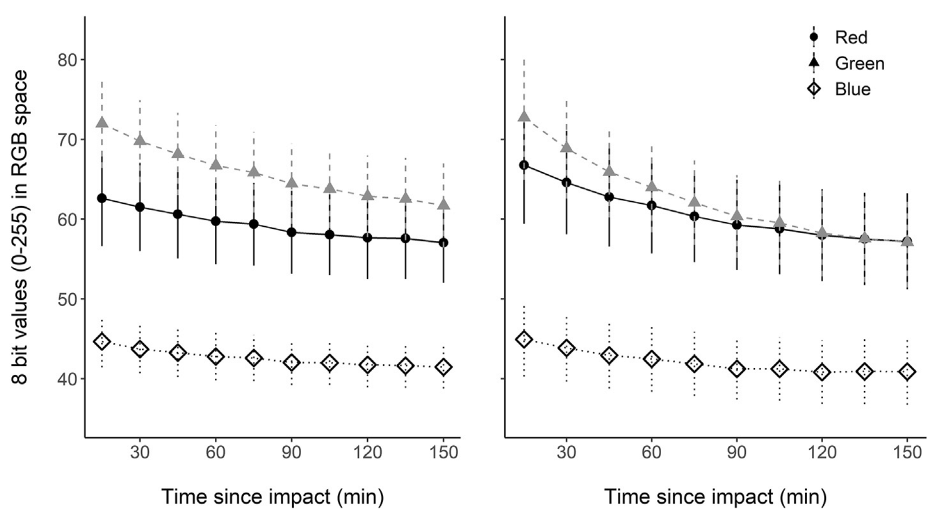

Fig. 9 – Temporal evolution of bruising colour in RGB colour space, post impact, for 'Hojiblanca' (left) and 'Manzanilla' (right) varieties measured from the images. Dots indicate the means values and upper-lower lines indicate the standard deviation.

4. Discussion

Within each variety, the size of the fruit detached was not related to the harvesting method used, except in the case of manual detachment using sticks (Table 2). The basis of this method is impact on the bearing branches, which has a higher incidence on larger fruit and therefore a lower fruit detachment force by mass ratio (Famiani et al., 2014). Our observations showed that the circularity of the harvested fruit is significantly different with manual methods (manual and stick beating) than with mechanised methods (branch shaker and shaker comb) for the same variety. In almost all cases, the size and shape of the varieties was significantly different due to their own physiology (Belaj, Satovic, Rallo, & Trujillo, 2002). There was a strong relationship between geometry and fruit mass, which other authors have already indicated (Ponce, Aquino, Millán, & Andújar, 2018). The number of spots on the harvested fruit showed the clear difference between manual and mechanised harvesting in the process of fruit detachment, in addition to indicating how interception with a net increases the amount of damage (Table 3), suggesting the need to address fruit interception with padded harvesting systems (Plasquy, Sola-Guirado, del Carmen-Florido, García & Blanco-Roldán, 2019; Ravetti & Robb, 2010). The average diameter of the spots caused by the different methods seems to be a determining factor for their characterisation, depending exclusively on the detachment method, with significant differences observed for 'Manzanilla' and 'Hojiblanca' between the manual, branch shaker and shaker comb methods, and for

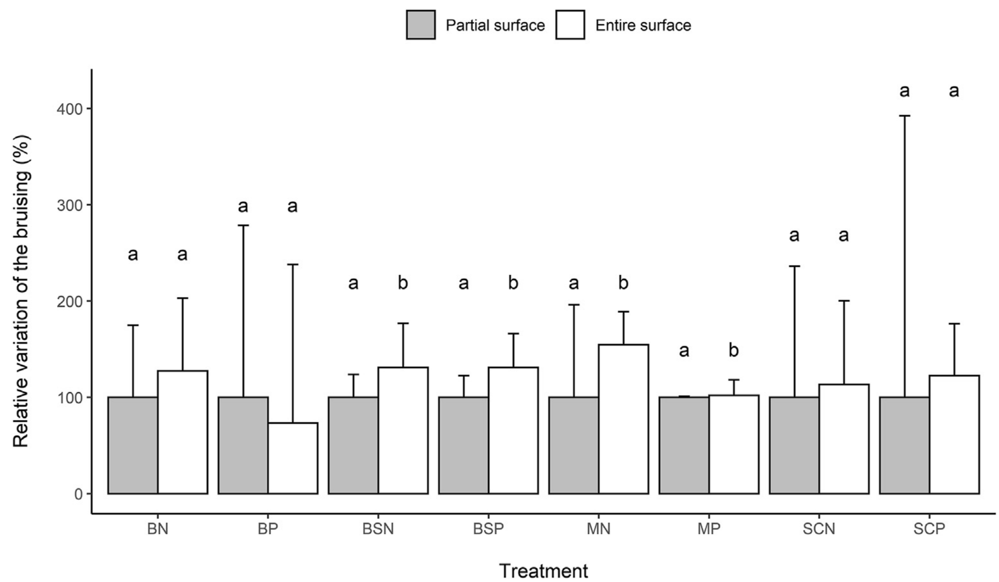

Fig. 10 – Relative variation of the bruising for each treatment of fruit detachment (M: manual by hand, BS: branch shaker, SC: shaker comb, B: manual beating) and interception (N: nets, P: padding) between one side of the fruit (grey) and the whole fruit (white). The bruising evaluated on one side was set as 100%. Different letters indicate differences within the same treatment between different observed surfaces (Wilcoxon Mann–Whitney rank sum test, $p < 0.05$).

varieties (Table 3). For the 'Manzanilla' variety, if we compare the diameters obtained with padded-surface versus netting interception, we observe that when padding is used, the diameter is reduced for all harvesting methods, except for stick beating, where the diameter remains very similar. In addition, when net interception is used there is a change in the shape of the spot, indicated by a decrease in circularity, whereas the spots in shaker comb and stick beating (Table 3) are more elongated. This may be due to the operation of the latter systems, which put the rods in direct contact with the fruit and branches.

Fruit firmness is a quality attribute for table olives. High firmness values favour a decrease in fruit damage by having lower deformation values on impact, which ultimately influence the distribution of fruit cell damage (Jiménez, Rallo, Rapoport, & Suárez, 2016). The results obtained confirmed this where 'Hojiblanca', with higher firmness values, suffered less damage compared to 'Manzanilla'. Cuticle thickness may therefore be an indicator of the table olive cultivars that are suitable for mechanical harvesting (Goldental-Cohen et al., 2019). In our work, we observed no differences dependent on harvesting method for fruit firmness in the bruising area, however, there were differences in the firmness of fruit harvested by hand compared with other harvesting methods, as other authors have observed (Morales-Sillero, Rallo, Jiménez, Casanova, & Suárez, 2014). In the case of 'Manzanilla', with a higher stone pulp ratio, there were differences when using the branch shaker and shaker comb, and it is the fruit harvested with the latter method that showed the lowest firmness. It seems that fruit with a higher bruise index, as in the case of harvesting with the shaker comb, had a lower firmness although we did not obtain significant correlations. Differences in firmness as the harvesting season progresses may indicate that fruit increases in size and, after the first growth phase, the concentration of solutes and water loss continues, which results in a greater susceptibility of the fruit skin to mechanical damage (Kiliçkan & Güner, 2008). Therefore, ascertaining the optimal harvesting period for this fruit is so important, as the aim is to obtain fruit with greatest size and rigidity, but without excessive fruit detachment forces that reduce the harvesting efficiency of mechanical systems.

Fruit colours measured in CIELAB space were slightly different between varieties, which indicates that colour may be another interesting discretisation factor between varieties. The higher values observed for 'Manzanilla' indicate brighter fruit and straw-green tones, while the lower values of 'Hojiblanca' result in darker fruit with bluish-green tones. When switching from manual to mechanised harvesting, the values in the 'a' channel increased and those in the 'L' and 'b' channels decreased, showing a significant difference in the 'b' channel, in accordance with the reports of Morales-Sillero et al. (2014). This variation, mainly in the green tone of the fruit, may result from the greater number of brown spots due to the use of mechanical harvesting, which produces a significantly different colour compared to the rest of the fruit (Riquelme et al., 2008) as seen in the controlled energy method (H) (Table 4). This also suggests that colour is an interesting control parameter for measuring the level of damage in fruits as a function that considers the percentages of green or browning, as reported by Goldental-Cohen et al. (2019). However, it is important to note that this is only possible for fruits at a specific stage of maturity since colour evolves throughout the harvesting season (Fig. 4) as reported by Sola-Guirado, Bayano-Tejero, et al. (2020).

'Manzanilla' was more susceptible to bruising and had higher bruise index values in all cases, as Jiménez-Jiménez, Castro-García, Blanco-Roldán, González-Sánchez, and Gil-Ribes (2013) reported in a drop test. There were differences in the bruise index between the harvesting systems studied and for the varieties, and this is clearly higher for the shaker comb due to the direct contact of the rods with the foliage. Thus, the bruise index can also be a control parameter for evaluation of the harvesting system used on fruit. It is important to note that this index considers the area of fruit damaged in relation to the area of the fruit, but not the depth measured by the volume of fruit bruising, which would require other types of evaluation techniques (Jiménez-Jiménez, Castro-García, Blanco-Roldán, Ferguson, et al., 2013; Morales-Sillero et al., 2014). The bruise index is related with the level of energy applied on fruit, such that lower energy levels will result in lower levels of damage (Jiménez-Jiménez et al., 2012). However, the energy levels required for table olives, are higher than those used for harvesting olives for oil (Sola-Guirado et al., 2014), due to an earlier harvesting (Famiani et al., 2014). In fact, to improve harvest efficiency, it is often necessary to use a combination of systems, such as trunk shakers with auxiliary harvesting systems (Zipori, Dag, Tugendhaft, & Birger, 2014). Moreover, when the energy received to detach fruit is added to the potential energy of the drop, damage is even greater, as observed in this work when the drop is over a net (Fig. 5). The relationship between the increase in bruising and height of fall, and with the contact surface (Saracoglu et al., 2011) again indicates the importance of studying interception systems in fresh fruit harvesting (Hussein et al., 2020), especially in 'Manzanilla'. This is even more the case when using management and cleaning systems on harvesters, which cause increased fruit damage (Sola-Guirado, Castillo-Ruiz, et al., 2020). Figure 7 shows the quantitative difference in damage by category according to severity. With net interception, the percentages of sound and slightly damaged fruit decrease and those of the other categories increase compared to padding interception, which is especially noticeable for the shaker comb. This classification of the bruise index according to severity of damage may be of major interest since with low levels of damage it is possible to reverse browning by pre-treatment with a diluted solution of NaOH, the use of cold (Zipori et al., 2014; Campus et al., 2018) or a nitrogen atmosphere (Segovia-Bravo, García-García, López-López, & Garrido-Fernández, 2012). In this way, minor damage can be minimised, and it is possible to reduce other damage in postharvest, as reported by Zipori et al. (2021). It is important to know how damage evolves over time in order to apply post-harvest treatments judiciously. Figure 8 shows how, at approximately 150 min after harvesting, the area of visible damage stops growing and stabilises, coinciding with the reports of Jimenez–Jimenez et al. (2013a), although damage continues to evolve internally up to 24 h (Jiménez et al., 2016). 'Hojiblanca' follows the same trend, although from the onset of impact its damaged area is smaller. We also observe an evolution of spot colour, which starts as dark green and transforms to brown (Fig. 9, in RGB space) (Table 4, in CIELAB space). These colour changes also differed between varieties, with a greater incidence in the green and red channels of RGB space. All of which indicates that the first hour is key to reduce the damaged area by application of the corresponding treatments (Segovia-Bravo, García-García, López-López, & Garrido-Fernández, 2011).

Part of the objective of this work is to characterise the bruise pattern of harvested green olives. It is a complex task to quantify the real amount of external bruising on a fruit or batches of fruit from a single photograph using computer vision because only a portion of the surface is perceived and, moreover, this is as a two-dimensional projection. The latter problem can be partially solved by correcting the projection (Mon & ZarAung, 2020). To maximise the sampled area per fruit, it is common to use mirrors (Reese, Lefcourt, Kim, & Lo, 2009), more than one camera (Xul, Zou, & Zhao, 2008) or rotating mechanisms (Cubero et al., 2014). These methods improve the estimated value with respect to the real value, allowing analysis of the whole or almost the whole the fruit surface. This work used a turning mechanism to observe the entire surface of the olive in order to estimate what percentage of information is lost when using a single photograph. The differences found for the harvesting methods tested may be due to the way in which they detach the fruit. With the shaker comb and beating, impacts on the olive can be produced by direct contact, generating a more heterogeneous punctual damage, and the value estimated with a single photo may be more conditioned by the part of the olive that is visible. However, the branch shaker, which acts directly on the branch and causes fruit detachment by vibration transmission, may produce damage, caused by some fruit hitting against others or against the branches and leaves, that is more homogeneous and distributed over the whole surface of the fruit. It is important to note that the percentage of bruising is a relative measure and depends on the amount of damage, i.e. the sum of the various bruise areas divided by the surface area of the fruit sampled. For this reason, the percentage of bruising on a fruit obtained from a single photograph may be higher than that obtained from the composite of the spread external surface, which only occurs for the beating method with padding. Therefore, it would be advisable to multiply the bruising value obtained from a single image by a value greater than 1 to provide a more realistic value for the bruising.

In terms of image processing requirements and time, the method used to obtain segmentation of the bruised areas requires a high manual component and therefore high consumption of time. Some improvements achieve better processing times, as is the case with machine learning techniques, but generate uncertainty (Sola-Guirado, Bayano-Tejero, et al., 2020). However, the manual method of analysis is the most suitable to obtain higher accuracy of results in the characterisation of fruit bruising. In this aspect, the spectrum used for the analysis is determinant because the results obtained in olives may differ when using RGB space colour (Jiménez-Jiménez, Castro-García, Blanco-Roldán, González-Sánchez, & Gil-Ribes, 2013), a combination of HSV and RGB (Riquelme et al., 2008) or another spectrum such as near infrared (Jiménez-Jiménez et al., 2012; Stella et al., 2015).

The results obtained in this study are especially interesting for pre- or post-harvest decision-making in olive farm management. For instance, deployed in systems on board machinery, some of the parameters characterised in this paper that are determined by computer vision systems could perform harvest estimates without the need for weighing by assigning a mass unit per fruit according to geometric or varietal parameters (Table 2). Another application, in industrial processing systems, could be determination of the amount and provenance of damage in terms of the harvesting system employed. The influence of factors involved in the process could serve to improve new mechanised harvesting systems and, in addition, help the farmer choose the most suitable one according to his conditions. Furthermore, it may influence industrial processing, since it facilitates an improved visual aspect of the olive after harvest, depending on the level of damage caused and the time of transport. Current marketing standards for certain parameters such as external defects set by tolerance are not yet demanding, but these parameters will develop and will, almost certainly, require further details in the future. Therefore, the application of techniques based on computer vision to obtain the largest number of olive parameters (Guzmán et al., 2015; Martínez Satorres, Martínez Gila, Beyaz, Gómez Ortega, & Gámez García, 2018; Ponce et al., 2018; Puerto, Gila, García, & Ortega, 2015) will be a reality in the industrial field in coming years.

5. Conclusions

This work reported the qualitative and quantitative knowledge of fruit and fruit bruising according to the type of harvesting system used. Different olive bruise patterns have been found depending on the harvesting system used. There are differences in the fruit morphological parameters of the 'Hojiblanca' and 'Manzanilla' varieties in parameters such as mass, length, diameter and circularity. The parameters of shape (circularity of Feret diameter) and number of spots can be useful descriptors to differentiate between the harvesting systems studied, with a strong differentiation between manual and mechanised harvesting. The firmness in the bruised area is lower than in the rest of the fruit, being significantly different between hand and mechanised harvesting methods. The colour b-value (cieLAB) can discern between manual and mechanised harvesting. The 'Manzanilla' variety has a greater damage than 'Hojiblanca' in all the cases studied, and the branch shaker system is the one that produced the greatest damage to the fruit, in general. The number of damages is significantly higher when fruit interception is carried out on nets than when a padded system is used. A numerical quantification of the bruise index according to various categories has been proposed. With this classification, each harvesting system has a different distribution of the damage it generates. A study of the bruise from the composite of the fruit spread external surface has been carried out and it has been identified that the amount of damage differs from that considered with the common method of one zenithal image of the fruit.

Funding for open access charge

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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.

Acknowledgements

Innolivar Project, - Public Purchase of Innovation in its Precommercial modality-, in accordance with the Agreement established between the former Ministry of Economy, Industry and Competitiveness (current Ministry of Science, Innovation) and the University of Cordoba, 80% co-financed by FEDER funds, within the Pluri-regional Operative Program of Spain 2014–2020. We would also like to thank the financial support provided by the Interprofessional Organisation of Table Olive and Olive Oil, Spain https://interaceituna.com/. The authors would like to thank Juan Pérez Moya for his technical support.

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