



# Impact of industrial shelling and blanching on almond kernel integrity and color

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## ABSTRACT

Spanish almond industry expressed concerns over increasing kernel breakage during processing, particularly with the new almond cultivars introduced since 2005. This research aimed to (i) evaluate kernel breakage across different almond cultivars during shelling and blanching in Spanish industrial machines; (ii) identify the main factors contributing to breakage; and (iii) assess the impact of blanching on kernel color. Shelling breakage was lower in 'Belona' (2%) than 'Guara' (7%), potentially attributed to its higher water absorption and round shape. However, blanching, drastically increased breakage in 'Belona' (42%) compared to 'Guara' (29%). A large variability among cultivars ('Carmel' 12%, 'Belona 2' 32% significantly similar to 'Guara' 29%, and 'Lauranne' 43% significantly similar to 'Belona' 42%), was observed, but also between different batches of the same cultivar ('Belona' 42% and 'Belona 2' 32%), probably due to different growing conditions. 'Lauranne' and 'Belona' exhibited a higher tendency to produce halves, whereas 'Guara' produced more pieces. Kernel breakage during blanching was significantly correlated with kernel width ( $r = 0.57^{***}$ ), protein, ( $r = -0.83^{***}$ ), and fat content ( $r = 0.67^{***}$ ). Blanching significantly affected kernel color ('Carmel', 'Belona 2', 'Guara', 'Lauranne', 'Belona';  $\Delta E = 19, 14, 12, 11, 10$ , respectively) and was identified as a critical control point for breakage across the processing line.

## 1. Introduction

Almond fruit is a drupe composed by three main elements: the hull (outer green part or mesocarp), the shell (intermediate woody part or endocarp) and the internal kernel which is also composed by the skin (brown tegument) and the white seed (cotyledons and embryo) (Grundy, Lapsley, & Ellis, 2016). All these components are responsible for protecting the kernel from birds, insects, microorganisms, oxidation, but also for giving resistance to the kernel depending on each cultivar. However, different almond physical properties such as paper and stony shells texture, or elongated and spherical shapes together with the different chemical composition of almond cultivars have a significant impact on kernel breakage (Lipan et al., 2024; Romero, Dicenta, Miarnau, Batlle, & Chamakh, 2018; Socias i Company et al., 2017).

Currently, kernel breakage during processing represents one of the biggest challenges faced by the Spanish almond industry because broken kernels have a significantly narrower range of applications compared to whole kernels, limiting their use, and reducing their overall market value. For instance, the highest quality grade in Spain is (i) 'extra', followed by (ii) 'supreme', (iii) 'selected', (iv) 'unselected Valencias', (v) 'whole & broken' and (vi) 'pieces'. For the first three quality grades, the 'mechanical damage' accepted is 2%, 5%, and 10%, respectively, and the same thresholds are established also for 'halves and broken pieces' of these three levels (Almendrave, 2020). In addition, in terms of kernel conservation, the shelf-life of broken kernels is lower than that of whole kernels due to increased surface area exposure which makes them more prone to oxidation and microbial contamination (Almond Board of California, 2023; Lin et al., 2012). This problem of kernel breakage

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occurred mainly with the introduction of new almond cultivars in 2005, because traditional postharvest handling practices were not designed for such a varietal diversity, highlighting the need for postharvest handling optimization (Battie et al., 2017; Lipan et al., 2024).

This defect can be generated throughout the entire agronomic and production chain, from orchard management, harvesting handling, dehulling, shelling, and blanching. Almond processing involves significant mechanical stress, including compression, friction, and temperature fluctuations, which are necessary to release the kernel from the hull and the shell and remove the brown tegument during blanching (Shirmohammadi, Charrault, & Blencowe, 2018). For instance, shelling uses impact force from punched circular bars to induce fracture in the almond shell and easily release the kernel (Verdú, Izquierdo, & Company, 2017; Lipan et al., 2024). This high-impact forces exerted can lead to kernel damage. However, pre-soaking/wetting the almonds before shelling, to increase the moisture content and elasticity of the kernel, can help reduce mechanical stress (Verdú et al., 2017). The next important step in the almond industry is the blanching operation required to separate the skin from the kernel. This consists of soaking the kernels in hot water near the boiling point, followed by exposing the wet kernels to the concomitant action of rubber rollers that gently rub off the skins, and later removing them by an air stream (Verdú et al., 2017). The cumulative impacts from these processes can increase the probability of kernel breakage, affecting almond quality and process efficiency. Previous studies in pilot plant shelling operations concluded that almonds with a larger water absorption or a rounder shape were less prone to kernel breakage (Lipan et al., 2024). However, such studies were not yet carried out at the industrial level.

In general, information regarding kernel breakage and its occurrence in industrial conditions it is scarce. In addition, this is a matter of fact that kernel browning can be related to inner enzyme activity; thus, it is feasible that impacts can break down some cells releasing enzymes that promote color change after shelling and remain during blanching. Thus, optimizing the blanching operation is of utmost importance both for kernel breakage reduction and kernel quality. Over-blanching can lead to color alterations, while under-blanching struggle to completely remove the skin, requiring extra costs for reprocessing (Fisklements & Barrett, 2014); unblanched kernels can be removed by electronic sorter, but not all those imperfectly blanched, requiring a final manual sorting (Verdú et al., 2017).

Thus, kernel breakage during almond processing (shelling and blanching) poses a significant economic challenge to the Spanish almond industry, leading to reduced yields, increased processing costs, and decreased product quality. Considering these issues, this study aimed to address this critical problem by: (i) evaluating, for the first time, kernel breakage across different almond cultivars in Spanish industrial conditions; and (ii) identifying the main factors contributing to kernel breakage during industrial processing. Additionally, because color is an important parameter for the industry, the effect of blanching operation on color change in the blanched kernels was also studied.

This study tackles a critical issue for the Spanish almond industry. Traditional processing methods have struggled to accommodate the unique characteristics of newer cultivars, and this study is the first to systematically investigate kernel breakage in Spanish industrial machines. By evaluating kernel breakage across different cultivars directly in the industry and identifying the key factors contributing to this phenomenon, these findings offer new insights that will help optimize processing techniques and enhance product quality. This study not only fills a gap in the existing literature but also provides valuable data to address a pressing issue for the Spanish almond industry, with important implications for future crop management and processing strategies.

## 2. Materials and methods

### 2.1. Plant material

This research consisted of two experiments: *Experiment 1* in which the industrial shelling behavior of two almond cultivars ‘Belona’ and ‘Guara’ syn. ‘Tuono’ (Dicenta et al., 2015) was assessed, and *Experiment 2* in which the industrial blanching behavior of five almond batches was assessed: ‘Belona’ and ‘Guara’ syn. ‘Tuono’, a batch of ‘Belona’ from different origin called ‘Belona 2’, ‘Carmel’ and ‘Lauranne’. Each almond batch came from different origins, ‘Belona’ and ‘Belona 2’ were sourced from two different regions within the province of Lleida (Spain), *Les Garrigues* and *La Noguera*, respectively. ‘Guara’ came from *Campo de Borja*, province of Zaragoza (Spain), ‘Lauranne’ from Andalucía (Spain), and ‘Carmel’ came from California (USA).

### 2.2. Almond processing

#### 2.2.1. Almond shelling operation

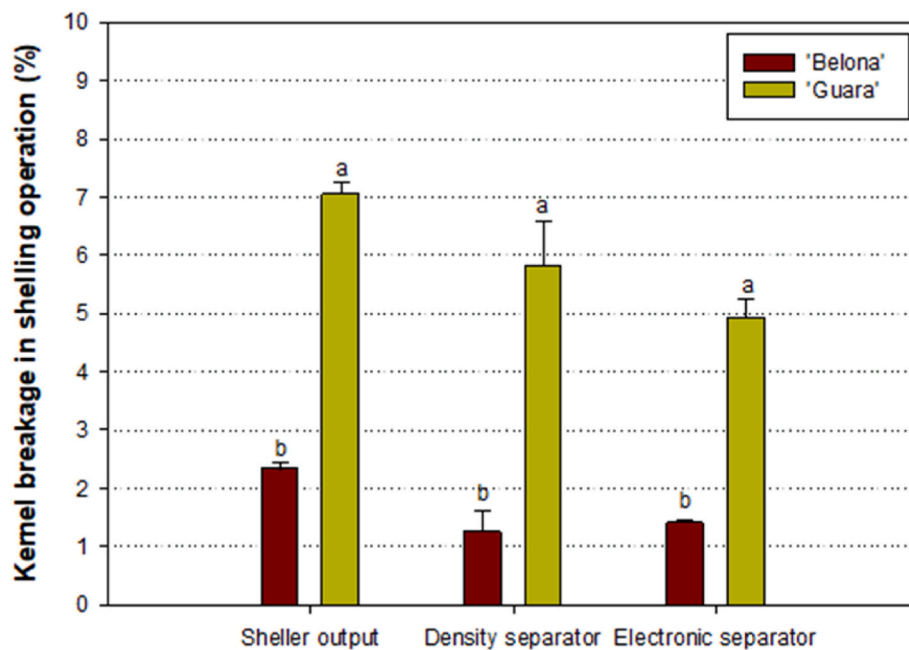
Almond shelling and kernel blanching was carried out in the facilities of the processor Almendras Martí located in Maials, (Lleida, Spain). The full almond shelling line was made by Borrell Machinery (Dénia, Alicante, Spain) to de-shell around 10 metric tons (10,000 kg) of almonds at once and consisted of almond conditioning system, shelling system, graders, shell-kernel separator, optic separator, and dryer. Prior to shelling, almonds underwent a water conditioning process. A screw conveyor system equipped with integrated spray nozzles was used to continuously hydrate the almonds, that were then transferred to holding silos for a predefined period before proceeding to the shelling stage. Previous laboratory experiments (data not shown) have demonstrated that water is able to penetrate the porous outer shell layer and then transitions to a vapor phase as it passes through the denser inner layer. Thus, after wetting, almonds rest in silos long enough to allow the diffusion of moisture into the kernel, increasing kernel elasticity and minimizing breakage during processing. Later the almonds are graded by size, and shelled using the Spanish shelling system previously described by Lipan et al. (2024).

#### 2.2.2. Kernel blanching operation

The full kernel blanching line was built by Maseto Technologies company based in Alicante (Spain) and was composed by blancher, peeler, dryer, cooler, optical sorter, and density separator. Approximately 1 metric ton (1000 kg) of kernels with skin were poured in the feeding hopper and underwent a washing process with cold water ( $18.9 \pm 1.04$  °C) before moving to the blancher. The almonds cultivated in Spain were blanched at 80 °C, while ‘Carmel’ was blanched at 90 °C, for 30 s each. After blanching, the kernels passed through abrasive rollers to remove the skin, followed by drying at 80 °C in a continuous four-layer belt dryer for 100 min and cooling. Then, skinned kernels proceeded to the optical and density sorter where kernels were separated into two bins, one for whole kernels and the other for halves and pieces. Finally, all the outputs (whole blanched kernels, broken blanched kernels, skin, rejects which include spoiled kernels and skin attached to the grain, and embryo’s radicles) were weighted and values were registered in industry batch record sheet for later traceability and yield calculations (Fig. 1S).

### 2.3. Sampling design

Samples were collected at regular intervals throughout the processing stages of both the shelling and blanching lines, with a specific design for each. In the shelling processing line, which consisted of 4 stages (i) initial dry almond; (ii) silo output; (iii) sheller output; (iv) density output; and (v) electronic output, samples were collected in triplicate at each stage. For the blanching processing line, which involved 12 stages (i) initial dry kernel, (ii) hopper output, (iii) cold water washing output, (iv) blanching output, (v) drying output, (vi) cooler entry, (vii) cooler



**Fig. 1.** Kernel breakage percentage in industrial shelling operation. Samples were collected in triplicate throughout the shelling operation steps: after shelling operation, after density separator, and after electronic separator. Different letters in each group of bars means significant differences ( $p < 0.05$ ) according to the Tukey's least significant difference test.

output, (viii) electronic separator entry, (ix) electronic separator output, (x) density separator output, (xi) whole kernel output and (xii) broken kernel output, sample frequency varied based on the importance and variability of each stage. Samples were collected in triplicate at the following stages: (i) initial dry kernel, (ii) hopper output, (v) drying output, (ix) electronic separator output, (x) density separator output, (xi) whole kernel output, and (xii) broken kernel output. Samples were collected in quadruplicate at stages deemed more critical or with greater variability, including (iii) cold water washing output, (iv) blanching output, (vi) cooler entry, (vii) cooler output, and (viii) electronic separator entry.

#### 2.4. Kernel breakage

Replicates of each sample collected in each stage of shelling and blanching processing line were subjected to physical and chemical analysis at IRTA Mas Bové facilities. The kernel breakage percentage was determined by visually inspecting a representative sample of 800 g per each replicate and the results of the kernel breakage are expressed in weight percentage.

#### 2.5. Moisture content

For the moisture content 10 kernels for each sample replication in duplicate were placed in pre-weighted aluminum tray and oven (Digatroni C-2005141 SELECTA, Abrera, Barcelona, Spain) dried at 103 °C to constant weight. The aluminum trays were directly cooled in a vacuum desiccator for 30 min and weighted. The moisture content was calculated based on almond weight before and after drying, and the results are expressed as grams of water per 100 g of sample on a wet basis (g/100 g).

#### 2.6. Water holding capacity and water absorption by almond shell powder and in-shell almonds

These determinations were made to obtain information about the capacity of each almond sample to retain water, as almonds conditioning is a compulsory step prior to almonds shelling in the Spanish in-

dustry. For each cultivar ('Belona' and 'Guara'), two independent shell samples were collected from the initial dry sample (before shelling operation). Water holding capacity (WHC) was determined in almond shell milled and sieved to particle size  $>500 \mu\text{m}$  according to the scientific literature (Lario et al., 2004; Robertson et al., 2000) with some modifications. Almond shell powder was dried in oven to remove all the moisture content and the aluminum trays were directly cooled in a vacuum desiccator for 30 min. Then, from each sample, 3 g of powdered shell substrate (dry sample) was hydrated in 30 mL of distilled water into three replicates Falcon tubes (45 mL volume), each tube was stirred for 1 min and kept at room temperature for 18 h. After equilibration, samples were centrifuged ( $2710 \times g$ ; 20 min), the supernatant was decanted carefully inverting the Falcon tube and leaving the pellet to drain in the tube, and the weight of the pellet was recorded (wet residue). This resulted in six replicates per cultivar for the WHC determination and the calculation was done using equation (1) and was expressed in g of water retained per g of ground almond shell.

$$\text{WHC} \left( \frac{\text{g}}{\text{g}} \right) = \frac{\text{wet residue (g)} - \text{dry sample (g)}}{\text{dry sample (g)}} \quad (1)$$

Besides WHC in almond shell powder, it was also considered important to measure the water absorption by the in-shell almond. For this method, 10 in-shell almonds were soaked for 18 h in a standardized volume of distilled water (200 mL), after which the remaining water was registered. This experiment was conducted in triplicate and the results are expressed in grams of water absorbed per 100 g of each sample (g/100 g).

#### 2.7. Morphological parameters and physical properties of almonds

Weight, length, width, and thickness were measured using digital caliper (Mitutoyo 500-197-20, Kawasaki, Japan) and a scale model AG204 Mettler Toledo (Barcelona, Spain) and the values were used to calculate geometric factors such as length to width ratio (L/W), geometric mean diameter (GMD), sphericity ( $\phi$ ), and surface area (S) as previously described by Lipan et al. (2024).

## 2.8. Almond blanching in laboratory

To determine whether almond kernel caliber (size) has an influence on its breakage, four calibers of ‘Belona’ (i) 12–13 mm, (ii) 13–14 mm, (iii) 14–16 mm and (iv) above 16 mm, were blanched in laboratory conditions. For the blanching experiment in laboratory, 25 almonds were blanched 1 min at 100 °C. After that, almonds were manually pilled, and dried in a stove 2 h at 70 °C. This process was carried out in triplicate and the kernel breakage percentage is expressed in percentage.

## 2.9. Color change in almonds after conditioning and blanching process

Color coordinates  $L^*$ ,  $a^*$  and  $b^*$  were determined with a MINOLTA CM-3500D colorimeter (Osaka, Japan) previously calibrated, using an 8 mm diameter viewing area, a D65 illuminant and a 2° observer as reference. The color change was calculated with the following equation (2):

$$\Delta E = ((L - L^*)^2 + (a - a^*)^2 + (b - b^*)^2)^{1/2} \quad (2)$$

where,  $L^*$ ,  $a^*$  and  $b^*$  represent the color coordinates values intern color of raw kernels, and  $L$ ,  $a$  and  $b$  represent the values of blanched kernels.

## 2.10. Chemical composition of almond kernels

For the chemical composition, two independent replicates of each cultivar were collected from the ‘whole kernel output’ stage. Protein, fat, fiber, and ash content were determined in triplicate for each replicate, resulting in a total of six measurements for each cultivar. The measurements were made according to AOAC methods as following. Almond kernels (30 g) were ground using a grinder model KN 295 Knifetec FOSS (Hillerød, Denmark) in 2 cycles of 5 s each. Fiber content of 1 g of ground almond was extracted and determined using ANKOM Fiber Analyzer model A200 (Macedon, USA). A filter bag (F57 also from ANKOM Technology 1915/1920) previously tared (W1) was used for the weighted sample (W2) and instantly sealed with a heat sealer from the same technology at approximately 0.5 cm from the bag opening. Besides the sample bag, other bags were also used as blank for digestion which were also previously tared (B) and weighted after digestion steps. Following the fat extraction that consisted of placing the bag into a 125 mL screw-cap flask with 99.5% acetone and stirred for 1 h. Once finished, the acetone was removed and the bags were oven (Model DIGITRONI C-2005141, SELECTA, Abrera, Barcelona, Spain) dried overnight at 103 °C. For sample digestion, the bags were placed in a bag suspender (ANKOM Technology #F11) with the acid solution ( $H_2SO_4$ , 0.255 mol/L) at 100 °C for 30 min under stirring. Then the solution was drained from the digester, and the bags were rinsed 3 times with 2 L of hot water (100 °C) under stirring conditions for 5 min. The bags were placed on filter paper to remove the excess of water and oven dried overnight in a crystallizer at 103 °C. Next day the bags were weighted (W3 for samples W3B for blank) and placed in porcelain cresols previously tared, and ashed in a muffle furnace (NABERTHERM Model LT 15/11/B180 28,865 Bremen, Germany) at 550 °C for 12 h (W4 for samples W4B for blank). The weight obtained after this process represents the total ash content. Thus, the fiber was calculated using the following equation:

$$Fiber (g / 100g) = \frac{(W3 - C1) - (W4 - C2)}{W2} \times 100 \quad (6)$$

$$C1 (g) = \frac{(W1 \times W3B)}{B} \quad (7)$$

$$C2 (g) = \frac{(W1 \times W4B)}{B} \quad (8)$$

where, W1 is the tared bag weight, W2 is sample weight, W3 is bag

weight after the digestion, W4 is the ash weight, C1 is the correction for bag loss during digestion, C2 is the correction for bag ash content, and B is the tare of the blank bag.

**Total protein content** was assessed by measuring the elemental nitrogen content using a Nitrogen Analyzer LECO Model FP-828p (St. Joseph, MI, USA). This method is based on the complete combustion of the sample in an  $O_2$  atmosphere, separation of nitrogen oxides from the other gases produced, reduction of the nitrogen oxides to molecular nitrogen ( $N_2$ ) and measurement of the nitrogen in a thermal conductivity cell. Between 0.15 and 0.10 g of ground almond was weighted in tin foil cones (502-186-200, LECO) previously tared, placed in the analyzer carousel and processed automatically. Then, the nitrogen content was converted to protein by multiplying a factor of 5.7 for vegetable material (Mariotti, Tome, & Mirand, 2008).

**Lipid content** was analyzed using a Soxhlet equipment Model SER 158 Solvent Auto Extraction (VELP, Usmate, MB, Italy). Extraction of 3 g (analytical balance model 5173, NAHITA BLUE) of ground almond was carried out for 1 h with thimbles immersed in boiling solvent (hexane) and another 1 h of reflux washing, followed by drying the extraction vessels (oven Model DIGITRONI C-2005141, SELECTA, Abrera, Barcelona, Spain at 85 °C for 30 min) and weighing the extracted crude fat.

## 2.11. Statistical analysis

One-way analysis of variance (ANOVA) was used to process the data, followed by Tukey’s HSD (honestly significant difference) multiple range tests to establish the significant differences among samples for the studied parameters. Statistically significant differences were considered when  $p < 0.05$ , and this threshold was applied consistently across all analyses. Significance levels were further refined with  $p < 0.01$ , and  $p < 0.001$ . These significance levels were marked with ANOVA stars \*, \*\*, and \*\*\*, where \* =  $p < 0.05$ , \*\* =  $p < 0.01$ , and \*\*\* =  $p < 0.001$ . These symbols indicate increasing levels of statistical significance, with lower p-values reflecting stronger significance. Pearson’s correlation coefficient was also run to assess the relationship between kernel breakage and the significant parameters. All analyses were run with SAS-Stat Software (V9.4. SAS Institute Inc., CA, USA).

## 3. Results and discussion

### 3.1. Experiment 1. Industrial shelling operation

#### 3.1.1. In-shell almond behavior in Spanish industrial cracking machines

For the first experiment, the kernel breakage was studied in different steps of the shelling operation and the results are shown in Fig. 1 (Tables 1S and 2S) and ranged from 1% to 2% in ‘Belona’, and from 5% to 7% in ‘Guara’. Other authors reported slightly higher results (4.6%) in industrial shelling operations for ‘Belona’ (Socias i Company & Felipe, 2007) while no data was found for ‘Guara’. A significant difference was found between the kernel breakage of these two cultivars, as indicated by Tukey’s test ( $p = 0.0001$ ), with ‘Belona’ registering the lowest kernel breakage at sheller output (2.33%) compared to ‘Guara’ (7.05%). This difference might be related to their physical characteristics, as presented in Table 1. The cultivar ‘Belona’, with the lowest kernel breakage after shelling operation, was characterized by a significant lower weight (3.6 g;  $p = 0.005$ ), length to width ratio (1.2;  $p = 0.0001$ ), and surface area (16 cm<sup>2</sup>;  $p = 0.033$ ), compared to ‘Guara’ (4.4 g, 1.6, and 17 cm<sup>2</sup>, respectively). Notably, the fruits of ‘Belona’ exhibited a significant rounder shape ( $p = 0.0001$ ), as indicated by a 9% higher sphericity value (75%) compared to ‘Guara’ (66%). Previous studies on kernel breakage in pilot plant shelling operation of 12 almond cultivars and interspecific hybrids reported sphericity values ranging from 62% to 80% and a negative correlation between this parameter and kernel breakage (Lipan et al., 2025). Authors reported that samples with higher sphericity (70–80%) reduced the kernel breakage, and the opposite was observed for samples with lower sphericity (62–69%). Although, other



**Table 1**  
Morphological parameters of in-shell almond and kernel for the 2 experiments.

|                    | Weight<br>(g)                                                     | Length<br>(mm) | Width<br>(mm) | Thickness<br>(mm) | Shell thickness<br>(mm) | Length/Width<br>ratio | GMD<br>(mm) | Sphericity<br>(%) | Surface area<br>(cm <sup>2</sup> ) |
|--------------------|-------------------------------------------------------------------|----------------|---------------|-------------------|-------------------------|-----------------------|-------------|-------------------|------------------------------------|
| Almond<br>cultivar | Experiment 1. Industrial shelling operation (in-shell almond)     |                |               |                   |                         |                       |             |                   |                                    |
|                    | ANOVA Test <sup>a</sup>                                           |                |               |                   |                         |                       |             |                   |                                    |
|                    | **                                                                | ***            | ***           | NS                | NS                      | ***                   | *           | ***               | *                                  |
| 'Belona'           | Tukey Multiple Range Test <sup>ab</sup>                           |                |               |                   |                         |                       |             |                   |                                    |
|                    | 3.59b                                                             | 30.2b          | 24.7a         | 15.4              | 3.02                    | 1.22b                 | 22.6b       | 74.8a             | 16.1b                              |
|                    | 4.37a                                                             | 35.6a          | 22.6b         | 15.9              | 2.99                    | 1.58a                 | 23.3a       | 65.7b             | 17.2a                              |
| Almond<br>cultivar | Experiment 2. Industrial blanching and peeling operation (kernel) |                |               |                   |                         |                       |             |                   |                                    |
|                    | ANOVA Test <sup>a</sup>                                           |                |               |                   |                         |                       |             |                   |                                    |
|                    | ***                                                               | ***            | ***           | ***               | —                       | ***                   | ***         | ***               | ***                                |
| 'Belona'           | Tukey Multiple Range Test <sup>ab</sup>                           |                |               |                   |                         |                       |             |                   |                                    |
|                    | 1.27 ab                                                           | 23.8b          | 16.0a         | 6.70bc            | —                       | 1.48c                 | 13.7a       | 57.5 ab           | 5.87a                              |
|                    | 1.22b                                                             | 26.0a          | 13.8cd        | 7.08b             | —                       | 1.90a                 | 13.6a       | 52.5c             | 5.84a                              |
| 'Belona 2'         | 1.06c                                                             | 21.6c          | 14.9b         | 6.33c             | —                       | 1.45c                 | 12.7b       | 58.7a             | 5.05b                              |
| 'Carmel'           | 1.39a                                                             | 25.2a          | 13.4d         | 8.20a             | —                       | 1.89a                 | 14.0a       | 55.8b             | 6.19a                              |
| 'Lauranne'         | 1.36 ab                                                           | 23.8b          | 14.2c         | 8.23a             | —                       | 1.68b                 | 14.0a       | 59.1a             | 6.21a                              |

<sup>a</sup> NS = not significant at  $p < 0.05$ ; \*, \*\*, and \*\*\*, significant at  $p < 0.05$ , 0.01, and 0.001, respectively.  
<sup>b</sup> Values (mean of 25 replications) followed by different letter, within the same column were significantly different ( $p < 0.05$ ), according to the Tukey's least significant difference test. GMD = geometric mean diameter.

**Table 2**  
Pearson's correlation coefficient (r) between kernel breakage and morphological parameters.

| Variables                       | Kernel breakage<br>(%) | Weight (g) | Length<br>(mm) | Width (mm) | Thickness<br>(mm) | L/W       | GMD (mm) | Sphericity<br>(%) | Surface area<br>(cm <sup>2</sup> ) |
|---------------------------------|------------------------|------------|----------------|------------|-------------------|-----------|----------|-------------------|------------------------------------|
| Kernel breakage<br>(%)          | 1                      |            |                |            |                   |           |          |                   |                                    |
| Weight (g)                      | −0.260                 | 1          |                |            |                   |           |          |                   |                                    |
| Length (mm)                     | −0.407*                | 0.605***   | 1              |            |                   |           |          |                   |                                    |
| Width (mm)                      | 0.567***               | −0.172     | −0.427*        | 1          |                   |           |          |                   |                                    |
| Thickness (mm)                  | −0.378*                | 0.816***   | 0.446**        | −0.550***  | 1                 |           |          |                   |                                    |
| L/W                             | −0.584***              | 0.445***   | 0.850***       | −0.836***  | 0.565***          | 1         |          |                   |                                    |
| GMD (mm)                        | −0.239                 | 0.949***   | 0.694***       | −0.174     | 0.822***          | 0.499**   | 1        |                   |                                    |
| Sphericity (%)                  | 0.352*                 | −0.048     | −0.798***      | 0.418*     | 0.084             | −0.742*** | −0.124   | 1                 |                                    |
| Surface area (cm <sup>2</sup> ) | −0.247                 | 0.952***   | 0.697***       | −0.181     | 0.824***          | 0.505**   | 0.999*** | −0.129            | 1                                  |

† = \*, \*\*, \*\*\*, significant at  $p < 0.05$ , 0.01, and 0.001, respectively. L/W = length to width ratio. GMD = Geometric mean diameter.

parameters such as almond shell texture, moisture or water absorption capacity, skin percentage and chemical composition of kernel were also highly correlated with the kernel breakage in pilot plant shelling operation. Lipan et al., 2025, also worked with ‘Guara’ cultivar, and reported different physical properties than those obtained in this study; for instance, the length to width ratio, sphericity and surface area were 1.3, 75% and 15 cm<sup>2</sup>, respectively. Also, the kernel breakage reported was around 45%, compared to the present study (7%). These variations that occurred in the same almond cultivar can be attributed to different factors of the sample source, including geographical origin, soil fertility, agricultural practices, harvesting time, etc. On the other hand, the significant differences in kernel breakage observed in the previous study likely stem from the authors’ primary focus on evaluating cultivar performance under identical conditions in a pilot plant shelling operation, rather than minimizing kernel breakage. Whereas the present study provides a representative sample of the shelling process at the industrial level in which reducing kernel breakage is a priority.

As observed, the almond shape is one of the most important parameters that might influence on kernel breakage and occurs because the shelling system in Spanish almond industry was originally designed for the Spanish native cultivar ‘Marcona’, which has a round shape. However, in the same study it was reported that between 2 round shape samples, one suffered approximately 15% more kernel breakage than the other; this fact was attributed to other factors such as the textural properties of the shell and its capacity to absorb water during the conditioning process.

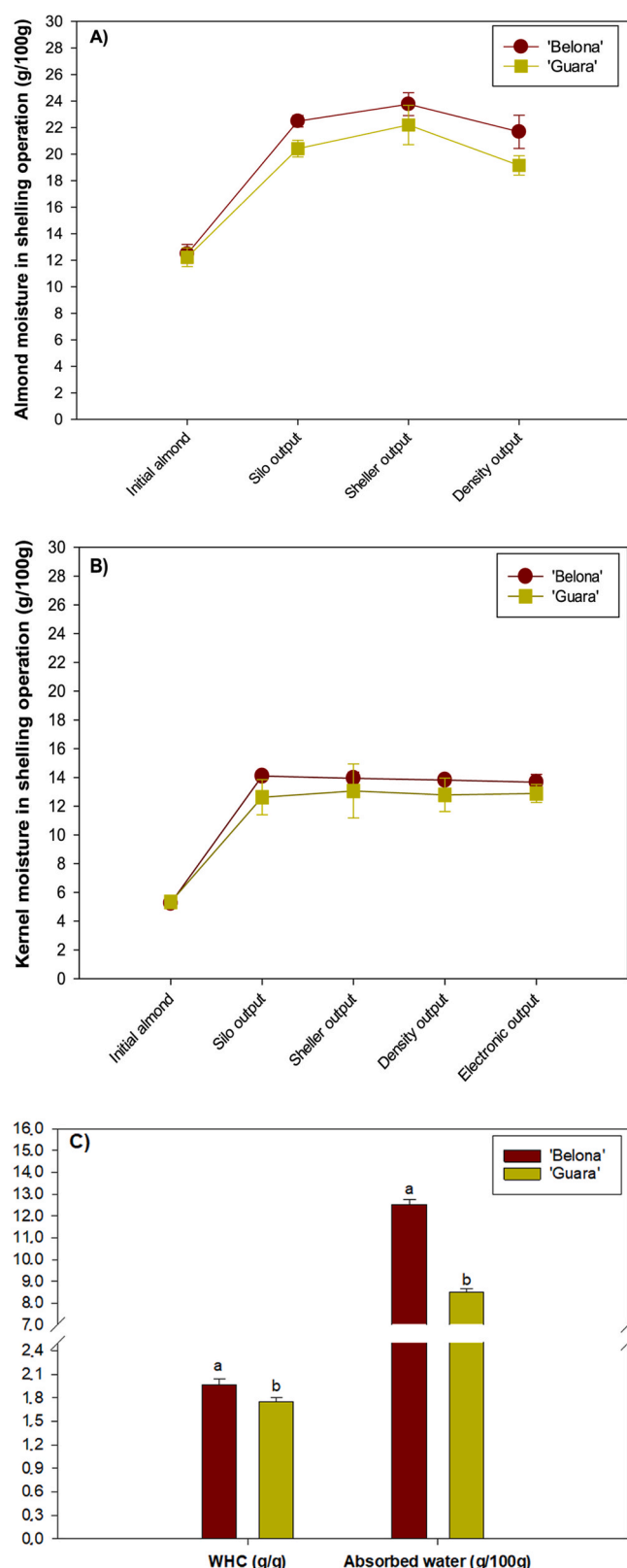
Therefore, Fig. 2 illustrates the moisture content at each shelling stage for both in-shell almonds (A) and kernels (B), as well as the water absorption characteristics of almonds (C). The initial moisture content

was 12 g/100g for the in-shell almonds and 5 g/100g for the kernels in both cultivars. After the water conditioning process, almonds significantly increased their moisture content both for in-shell almonds (22 g/100g) and kernels (13 g/100g). While the moisture content in the kernel was similar ( $p = 0.150$ ) for both cultivars along the shelling stages, for the in-shell almonds varied between the two cultivars; ‘Belona’ recorded a significantly ( $p = 0.031$ ) higher moisture content (23 g/100g) than ‘Guara’ (21 g/100g). This difference in shell moisture could be attributed to factors such as shell properties and permeability. Thus, water holding capacity of the almond shell powder and the absorbed water by the in-shell almonds were also assessed and the results are shown in Fig. 2C. Regardless of the method used to measure the water absorption capacity by almonds, the results were consistent, showing that cultivar ‘Belona’ exhibited a significantly ( $p = 0.0001$ ) higher water holding capacity (1.96 g of water/g of almond shell powder with a particle size <500 μm) and absorbed water (12.5 g/100g) compared to ‘Guara’ (1.75 g/g and 8.50 g/100g, respectively). These results corroborate those of moisture content of in-shell almonds and made evident that ‘Belona’ cultivar from this trial was able to absorb more water than ‘Guara’ which might have diminished shell hardness and consequently helped to reduce the kernel breakage.

### 3.2. Experiment 2. Industrial blanching and peeling operation

#### 3.2.1. Cultivars ‘Belona’ and ‘Guara’ performance in blanching operation

Subsequent to shelling operation, almonds undergo a blanching process to remove the tegument (skin), thereby preparing the kernel for further processing. For blanching operation, five almond samples (from 4 cultivars) were evaluated in terms of kernel breakage and physical



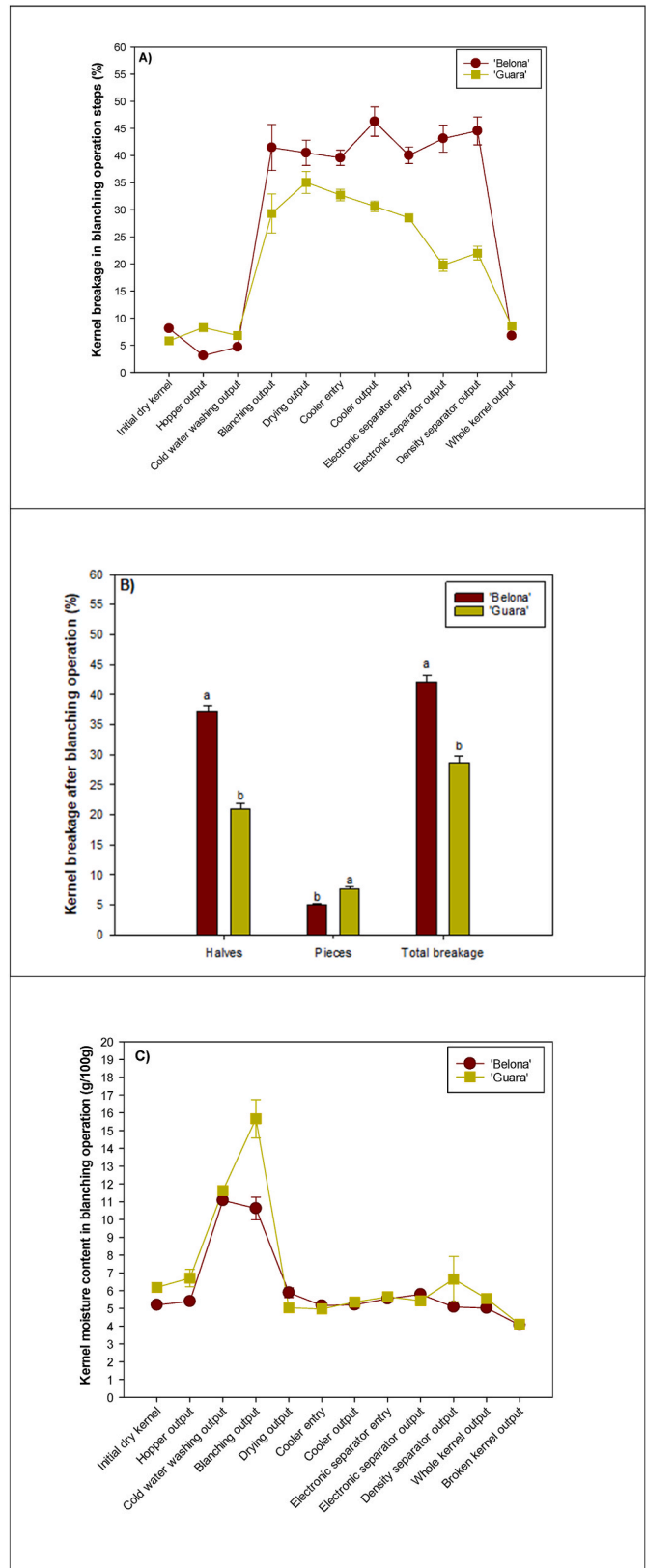
**Fig. 2.** Moisture content of in-shell almonds (A) and kernels (B) processed in industrial conditions. Samples were collected in triplicate throughout the shelling operation steps: (i) initial almond, samples collected before the conditioning process (dry); (ii) silo output, after the conditioning process (wet); (iii) sheller output, after cracking; (iv) density separator output; and (v) after electronic separator output. Fig. 2 C refers to water holding capacity (WHC) values of almond shell powders (mean of 6 replications), and absorbed water by the in-shell almonds after 18 h of soaking in triplicate.

characteristics. Two of them belonged to the same batches of 'Belona' and 'Guara' assessed in the 1st experiment, and the other three consisted of another batch of 'Belona' called 'Belona 2', 'Carmel' and 'Lauranne'. Fig. 3 (Table 3S) graphically depicts kernel breakage and moisture content at each of the 11 stages of the blanching operation, specifically for the samples processed in the 1st experiment. Considering the average breakage of the kernel of the first 3 steps (initial, hopper, and cold-water washing outputs) before blanching, 'Belona' registered significantly ( $p = 0.043$ ) lower values (5%) than 'Guara' (7%). This was somehow expected, after knowing the results of the shelling operation in which 'Guara' produced more broken kernels than 'Belona'. However, the breakage pattern shifted dramatically after blanching process, cultivar 'Belona' presented a significantly ( $p = 0.0001$ ) higher breakage rate (42%) than 'Guara' (29%) considering the average breaking of all steps after blanching. Broken kernels were also evaluated in the whole kernel output where is supposed that only whole kernels are collected (this represents the last step on the graphic). However, broken kernels were also found in this step, in which 'Guara' recorded significantly ( $p = 0.047$ ) higher values (9%) than 'Belona' (7%). This might occur because 'Belona' is more prone to split into halves (37%) compared to 'Guara' (20%), while 'Guara' tends to break into smaller pieces (8%) more frequently than 'Belona' (5%). These differences were statistically significant for both halves and pieces ( $p = 0.0001$ ), as shown in Fig. 3B. According to the scientific literature 'Guara' produces a high percentage (10–20%) of "doubles" or "twins" defect, while no incidence was reported for 'Belona' (Almond Board of California, 2020; Socias i Company & Felipe, 2007). This defect occurs when two or more embryos develop in a single ovary and are enclosed by the same shell, causing one side of the double kernel to be flat or concave (Batlle et al., 2017; Lipan et al., 2022). This irregular shape reduces its uses where the whole kernel is visible, or for high quality slices and might be also responsible for generating a lower number of halves than 'Belona' in the blanching operation.

The moisture content along the 12 steps during the blanching operation is presented in Fig. 3C. At the beginning of the process kernels of 'Belona' and 'Guara' started with a different ( $p = 0.004$ ) moisture content of 5 g/100g and 6 g/100g, respectively. During cold-water washing, both cultivars increased their moisture content to 11% ( $p > 0.05$ ). However, after blanching, while 'Belona' maintained its moisture content to 11 g/100g ( $p = 0.0001$ ), 'Guara' increased from 11 g/100g and 16 g/100g ( $p = 0.0001$ ). Drying operation dropped the moisture content of both samples back to 5% with no difference ( $p = 0.542$ ) between two cultivars at the end of the process.

### 3.2.2. Blanching aptitude of all five cultivars

Fig. 4 presents the kernel breakage and moisture content data for all five almond samples, comprising four cultivars and two batches of the same cultivar, following the blanching process. Kernel breakage in the initial almonds (Fig. 4A; Table 4S) ranged from 1.5% to 8.5% and showed significant differences among cultivars ( $p = 0.001$ ). Tukey's HSD test showed that 'Carmel' exhibited the lowest breakage rate, followed by 'Lauranne' (3.7%), while 'Belona' (5.3%) and 'Guara' (6.9%) registered similar and intermediate values. The highest breakage was recorded by 'Belona 2'. Similarly, as before, the situation changed after blanching operation for all samples by increasing the kernel breakage to a range of 12% and 43% with significant differences among all cultivars ( $p = 0.0001$ ). Cultivar 'Carmel' demonstrated consistently lower values of kernel breakage, and statistical tests indicated no significant difference between 'Guara' (29%) and 'Belona 2' (32%), nor between the 'Belona' (42%) and 'Lauranne' (43%), the samples with the highest incidence. At the end of the process, in the whole kernel bin, the broken kernels ranged between 1.6% and 11.3% with significant differences among cultivars ( $p = 0.0001$ ); 'Belona 2' registered the lowest amount, followed by 'Carmel' (4.8%), 'Belona' (6.7%) and 'Guara' (8.5%), while 'Lauranne' still registered the highest values of kernel breakage also at the end of the process in the whole kernel output. Lower kernel breakage



**Fig. 3.** Kernel breakage and moisture content of de-shelled almonds in industrial blanching operation: A) kernel breakage in each step of the blanching operation; B) average kernel breakage of the steps with most impact in broken kernel, separated in halves, pieces and total breakage; C) moisture content of samples in each step.

**Table 3**  
Chemical composition of blanched kernels of each cultivar used in experiment 2.

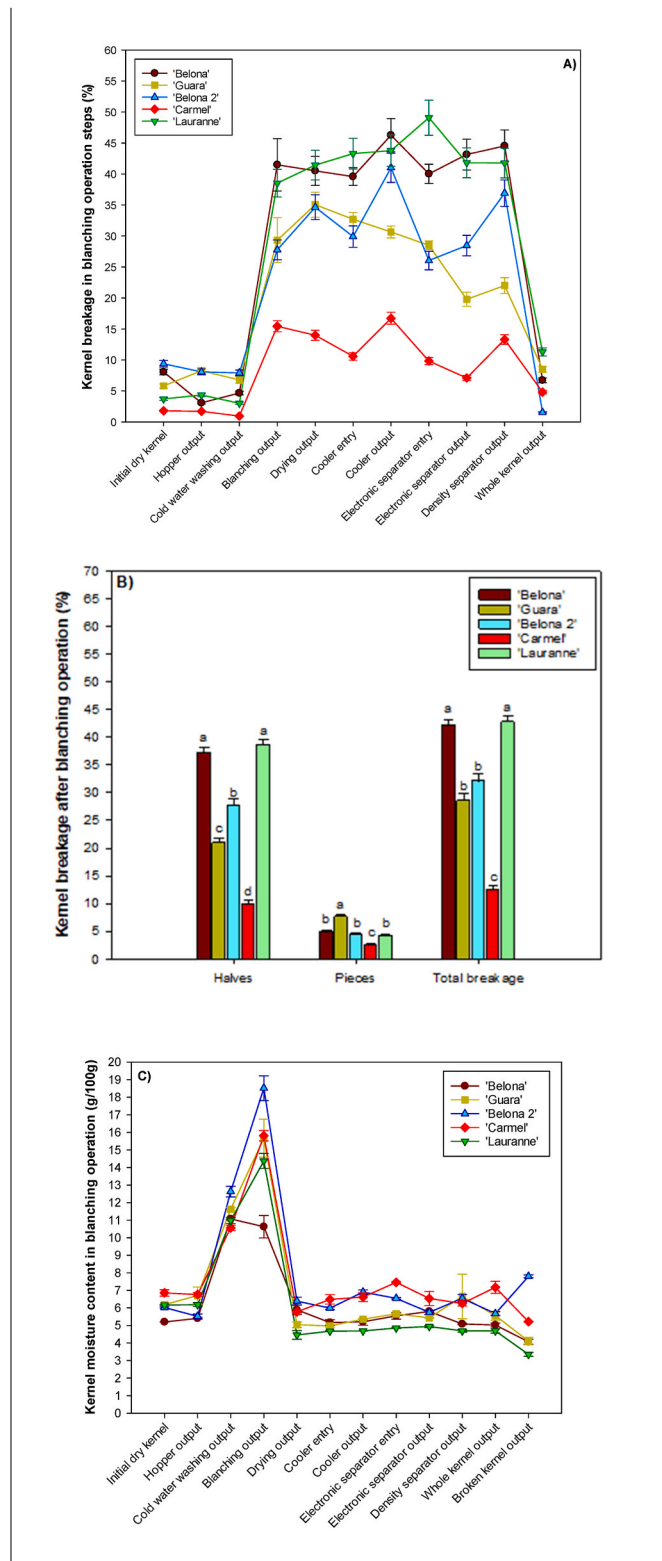
| Almond cultivar                        | Protein<br>(g/100g) | Fiber<br>(g/100g) | Ash<br>(g/100g) | Fat<br>(g/100g) |
|----------------------------------------|---------------------|-------------------|-----------------|-----------------|
| ANOVA Test <sup>a</sup>                |                     |                   |                 |                 |
| ***                                    |                     |                   |                 |                 |
| Tukey Multiple Range Test <sup>b</sup> |                     |                   |                 |                 |
| 'Belona'                               | 21.5e               | 4.52bc            | 2.98d           | 63.5a           |
| 'Guara'                                | 25.7b               | 3.46c             | 3.16b           | 56.9b           |
| 'Belona 2'                             | 23.2d               | 6.06b             | 2.93e           | 56.7b           |
| 'Carmel'                               | 28.7a               | 5.65b             | 3.04c           | 53.6c           |
| 'Lauranne'                             | 24.3c               | 8.87a             | 3.37a           | 56.7b           |

<sup>a</sup> = \*\*\* significant at  $p < 0.001$ , respectively.  
<sup>b</sup> Values (mean of 6 replications) followed by different letter, within the same column were significantly different ( $p < 0.05$ ), according to the Tukey's least significant difference test.

rates (23.6%) were reported for the same cultivar 'Belona' after industrial blanching operation (Socias i Company & Felipe, 2007). These reported results agree with the kernel breakage percentage of 'Belona 2' (but not with 'Belona'), calculated based on the industry record sheet (Fig. 1S), where the percentage of broken kernels was calculated relative to the initial weight of the sample (with skin), which is fed into the intake hopper. In Fig. 3A and 4A, the breakage percentage is calculated based on the total weight of the blanched sample. Kernel breakage for all five almond samples was also separated in halves and pieces to be able to understand how each cultivar breaks, the results are shown in Fig. 4B. Significant differences were observed among samples ( $p = 0.0001$ ) and the results showed that 'Lauranne' and 'Belona' are more susceptible to yield halves while, while 'Guara' is more prone to generate pieces. Overall, from all the studied cultivars 'Carmel' presented significantly lower broken kernels while the blanching-peeling stage represented the most critical point in the whole process for all samples.

3.2.3. Factors influencing the kernel breakage in blanching operation

3.2.3.1. Moisture content. Moisture content was also evaluated for all five batches in all steps of blanching operation and the results are presented in Fig. 4C. At the beginning of the process, samples were below 6 g/100g of moisture content in kernel, which increased to 11–13 g/100g after cold-water washing, and to 11–19 g/100g after the blanching process. The moisture was reduced again to 5–6 g/100g in the final product due to the needed drying process. Similar to the kernel breakage, each cultivar behaved differently, and even the same cultivar can exhibit variations between different batches; for instance, 'Belona' and 'Belona 2' started from similar moisture content, however after the blanching operation, 'Belona' from the shelling operation batch registered 11 g/100g moisture content, while 'Belona 2' almost doubled the value (19 g/100g) with significant differences between them ( $p = 0.004$ ). As expected, due to the similar drying conditions, both batches kept this tendency until the end of the process, 5.2 g/100g and 6.4 g/100g ( $p = 0.0001$ ), respectively. Evaluating the moisture content in the blanching stage where the almonds pass through the friction rollers to remove the skin, it can be observed that the samples with the lowest moisture content ('Belona' 11 g/100g and 'Lauranne' 14 g/100g) were the samples that most kernel breakage generated (42.3% and 42.8%, respectively) and vice versa. Pearson's correlation coefficient showed a negative correlation between kernel breakage and moisture content ( $r = -0.80$ ;  $p = 0.105$ ), although not significant. However, higher moisture content can increase kernel elasticity (Lipan et al., 2025; Shirmohammadia & Charraut, 2018), potentially leading to more ductile behavior when kernels pass through the friction rollers for peeling, contributing to the reduction of kernel breakage.



**Fig. 4.** Kernel breakage and moisture content of all samples in industrial blanching operation: A) kernel breakage in each step of the blanching operation; B) average kernel breakage of the steps with most impact in broken kernel, separated in halves, pieces and total breakage; C) moisture content of samples in each step.

**3.2.3.2. Physical properties.** Given the relevance of the morphological characteristics in the almond shelling process, it was sought to determine if these parameters could also influence kernel breakage during blanching operation. Table 1 presents the morphological parameters of almond kernels and exhibits how each cultivar presented different shapes; while 'Carmel' and 'Guara' are more elongated, 'Belona' and 'Lauranne' present a higher sphericity. Moreover, Table 2 exhibits the Pearson's correlations between the kernel breakage and these parameters. Significant correlations were found between the kernel breakage and length ( $r = -0.41$ ), width ( $r = 0.57$ ), thickness ( $r = -0.38$ ), length to width ( $r = -0.58$ ), and sphericity ( $r = 0.35$ ). This means that cultivars with more elongated kernel shape seemed to be more resistant to breakage, whereas kernel width might have a negative impact in blanching operation. To corroborate these results, 4 different calibers of 'Belona' were blanched in laboratory conditions and the results are presented in Fig. 5. Here also, higher calibers of the same cultivar tended to enhance kernel breakage, although this was not statistically significant at  $p < 0.05$  ( $p = 0.083$ ). These results agree with those from Table 2, because in Spain, the caliber of an almond specifically refers to its width, which was observed to be positively correlated with the kernel breakage. These findings have important implications for industry, suggesting that bigger calibers could be allocated for direct sale as raw or unprocessed kernels and smaller ones to blanching, avoiding in this way important economic losses generated by kernel breakage. Alternatively, a particular setup should be done in the shelling unit to adapt the pressure of the rules on the kernels with a bigger caliber. However, to confirm these findings and optimize industrial processes, this experiment should be directly validated in an industrial setting.

**3.2.3.3. Chemical composition.** To better understand the aptitude of each cultivar regarding the kernel breakage, other parameters such as chemical composition were also studied, and the results are presented in Table 3. Protein content ranged between 22 g/100g and 29 g/100g with significant differences among all 5 samples. 'Belona' (from the shelling operation experiment) was the sample with the lowest content, followed by the other batch of 'Belona 2' (23 g/100g), 'Lauranne' (24 g/100g), 'Guara' (26 g/100g), while 'Carmel' (29 g/100g) was the cultivar with the highest content. Fiber ranged from 3.5 g/100g to 8.9 g/100g being 'Guara' the sample with the lowest content and 'Lauranne' with the highest one. 'Belona', 'Carmel' and 'Belona 2' presented an intermediate value of 4.5 g/100g, 5.6 g/100g and 6.1 g/100g. Ash content also varied among samples and followed this order 'Belona 2' (2.93 g/100g), 'Belona' (2.98 g/100g), 'Carmel' (3.04 g/100g), 'Guara' (3.16 g/100g), and 'Lauranne' (3.37 g/100g). Moreover, sample 'Carmel' exhibited the lowest fat content (54 g/100g), followed by 'Guara', 'Belona 2' and 'Lauranne' with intermediate values of 57 g/100g, while 'Belona' presented the highest fat content of 64 g/100g. According to Pearson's correlation coefficient (Fig. 6) higher content of protein Fig. 6A ( $r = -0.825$ ;  $p < 0.0001$ ) and lower content of fat Fig. 6B ( $r = 0.674$ ;  $p < 0.0001$ ) seemed to reduce the kernel breakage at industrial blanching operations. In addition, no effect was observed for kernel fiber ( $r = 0.20$ ;  $p < 0.288$ ) and ash ( $r = 0.29$ ;  $p < 0.126$ ) contents. A previous study suggested that a higher fat content in kernels could reduce breakage during shelling operation, potentially due to increased kernel deformation ( $r = 0.71^{**}$ ) which may enhance the absorption of impact energy from the shelling hammer (Lipan et al., 2025). However, the present results indicate the opposite in the blanching operation; seems that almonds with higher fat content are more susceptible to kernel breakage after the blanching step. It must be considered that current results refer to different cultivars, each with a different fat content. Still, there may be other characteristics that could be the real origin of the breakage. In this regard, 'Belona 2' had lower fat content than 'Belona' and resulted in lower breakage, in favor of current results. These findings emphasize the need for comprehensive knowledge of each almond cultivar and its performance at every processing stage, to mitigate economic losses



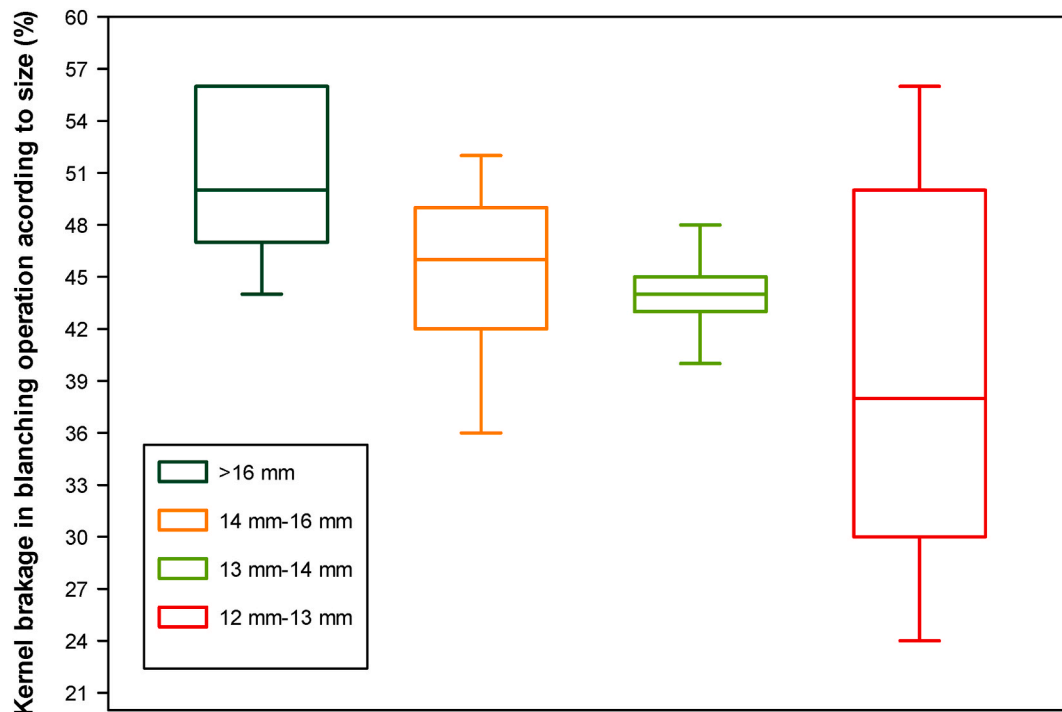


Fig. 5. Kernel size impact in almond kernel breakage (cv. 'Belona') in laboratory blanching operation.

caused by breakage.

#### 3.2.4. Blanching impact on kernel color

Color of blanched kernels was assessed in three stages: just after blanching and peeling, after drying, and in the final product. Blanching operation showed a significant impact on kernel color for each cultivar (Fig. 7; Table 5S). The highest color change was found in samples collected just after the blanching stage, and this was reduced with the drying process. It is important to highlight that after the blanching stage, the kernels become wet (moisture content between 11 g/100 g and 19 g/100 g depending on the cultivar), which reduces reflection and increases the transmission of light, resulting in a darker appearance (Pillinger, Ahmed, Bessenyei, & Kiss, 2023). After the drying stage, if the darker appearance stays it would not be due to water anymore, because as seen in Fig. 4C, at that stage moisture is reduced below 6 g/100 g. Regarding color change results, the most affected cultivar was 'Carmel' ( $\Delta E = 18.6$ ), followed by 'Belona 2' ( $\Delta E = 14.3$ ), 'Guara' and 'Lauranne' ( $\Delta E = 12.2$  and  $\Delta E = 11.3$ , respectively), while 'Belona' from the shelling operation batch was the less affected cultivar ( $\Delta E = 9.7$ ). As explained in materials and methods, 'Carmel' underwent a 10 °C temperature increase compared to the other cultivars, because at lower temperature conditions adequate peeling was not possible. It is worth mentioning that 'Carmel' cultivar contains a thinner skin tightly attached to the grain, results that can be easily deduced from the industry batch record sheet, values graphically represented in Fig. 1S. Higher temperature might be the main reason behind the color change increment of this cultivar. Authors working with the optimization of the roasting almond process of almonds reported a significant increase in color change ( $\Delta E$  of 8–12 and to 24) with an increase in roasting temperature (150 °C, 170 °C, and 190 °C, respectively) (Lipan, Cano-Lamadrid et al., 2020). As observed, the color change for 'Carmel' was closer to the color change of roasting at the highest temperature (190 °C), differences that can be related to unlike color measurement equipment and different almond cultivars. Regarding the other 4 batches blanched in the same conditions, there were also differences in color change among them. The biggest difference was found between the two batches of the same cultivar 'Belona'. Thus, besides blanching conditions, other factors,

including chemical composition (sugars, amino acids, fatty acids, pigments, etc.) might contribute to the color alteration. For instance, sucrose content in 'Carmel' was reported to be around 3.4%, sucrose, glucose and fructose content in 'Lauranne' was 3.6%, 6.5% and 3.5%, in 'Guara', 2.6%, 16% and 3.9%, respectively, and in 'Belona' total sugars were 5.2% (Lipan, García-Tejero, et al., 2020; Llompарт et al., 2024; Yada, Huang, & Lapsley, 2013). Similar with the amino acids which are also responsible for the color change under increased temperature (Serón et al., 1998). As well as the lower pH, moisture loss, pigments, and oxidation of ascorbic acid (Agila & Barringer, 2012; Nizamlioglu & Nas, 2016). This opens up an entirely new research line about cultivars and compositional influences on color change. Such knowledge will be invaluable to the almond industry, which consistently seeks for kernel enhanced whiteness and thus to improve quality.

#### 4. Conclusions

Kernel breakage and color changes are significant quality concerns for the Spanish almond industry, with increasing incidence in recent years. The introduction of new almond cultivars since 2005 has exacerbated this problem, as traditional postharvest handling practices may not be optimally suited for their unique characteristics. This is the first research that investigated kernel breakage across different cultivars during industrial shelling and blanching in the Spanish industry. Results demonstrated significant cultivar-dependent variability in breakage rates. Spanish almond cultivars ('Belona' and 'Guara') show a 5% difference in kernel breakage under the same shelling conditions. Differences that might be linked to physical properties, because higher water absorption during conditioning and a rounder almond can potentially reduce breakage in Spanish Borrell shellers. In addition, almond cultivars perform differently in shelling and blanching operations; for instance, 'Belona' showed lower kernel breakage than 'Guara' in shelling, but this trend drastically reverses in blanching, with a 13% difference between them. This study demonstrates that kernel breakage susceptibility varies considerably among cultivars, and even within the same cultivar from different origins. This underscores the need for a detailed understanding of each cultivar's performance throughout the

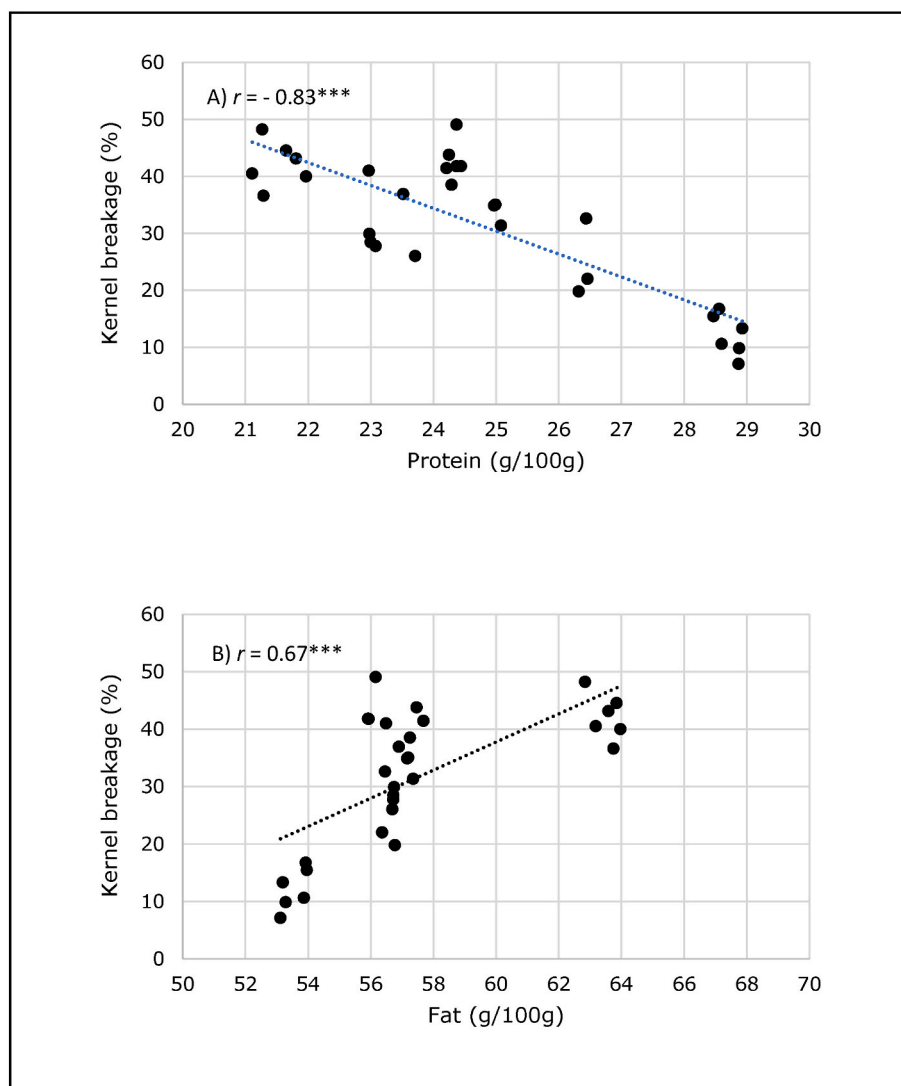


Fig. 6. Pearson's correlation coefficient ( $r$ ) between kernel breakage percentage in blanching operation and chemical composition: A) protein; B) fat.

processing line, but also for further research to understand the impact of their origin, agronomic practices, growing conditions, and postharvest handling on kernel breakage. In addition, the findings of this research emphasize the blanching-peeling stage as the most important critical control point for kernel breakage. As well as that almonds with higher width (caliber) and fat content are more prone to breakage during blanching, in contrast to those with higher protein content and an elongated shape, that seems to reduce this defect. Finally, for almond batches dedicated to applications where kernel color is a critical quality attribute, blanching conditions must be carefully controlled to achieve the desired color uniformity, because they have significant influence in color change.

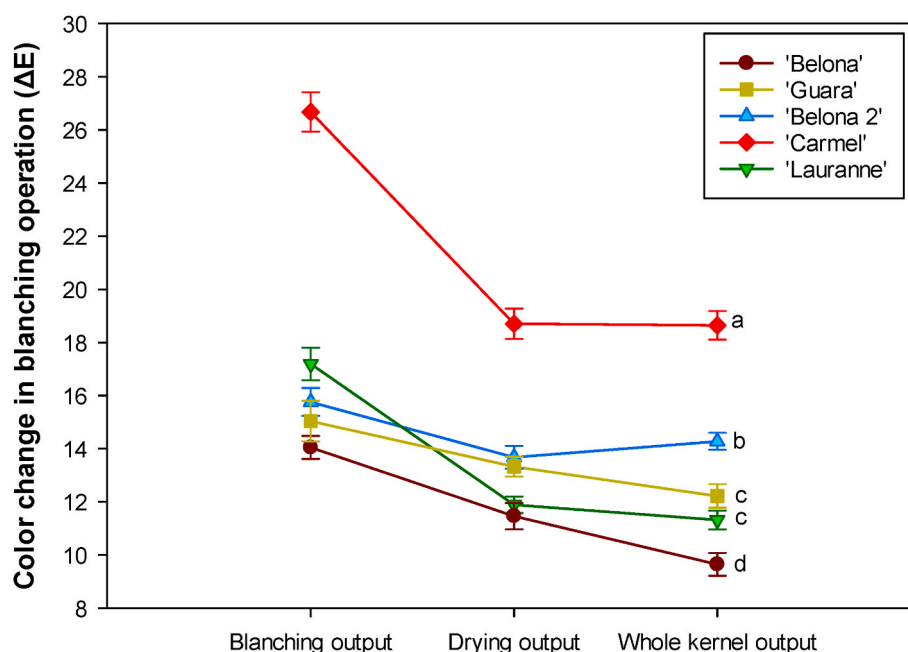
#### Limitations and future perspectives

This study provides valuable insights into kernel breakage during almond processing in Spanish industrial machines; however, several limitations should be noted. The primary constraint was the dependence on industry operations, which dictated the cultivars available for study. While we were able to analyze kernel breakage for 'Belona' and 'Guara' in both shelling and blanching, and additional cultivars ('Carmel,' 'Lauranne,' and a second batch of 'Belona 2') in blanching, the scope was limited to cultivars that were in demand at the time of the study. Cultivars such as 'Vairo' or widely grown American cultivars like

'Nonpareil' and 'Butte' could not be included, as their processing was not feasible under the industry's economic constraints. For example, the industry requires substantial quantities for processing (e.g., ~10 t for shelling or ~1 t for blanching), which were not achievable for these cultivars during the study period. Additionally, certain cultivars, like 'Nonpareil,' are processed in the United States with specialized equipment for paper-shelled almonds and arrive pre-shelled in Spain, making them unsuitable for evaluation in Spanish shelling machines. Despite these limitations, we believe that the cultivars studied represent a meaningful cross-section of the industry, as they include both American and newer European cultivars with significant market importance. Future studies could expand on this work by including a broader range of cultivars and investigating their performance in both shelling and blanching operations. Additionally, the development of new technologies and specialized machinery designed to process paper-shelled almonds could address a significant gap in the current processing infrastructure. These innovations, already emerging, represent a promising area for future exploration to enhance the efficiency and versatility of the Spanish almond industry, enabling it to handle a broader range of cultivars and meet evolving market demands.

#### CRediT authorship contribution statement

Leontina Lipan: Writing – review & editing, Writing – original draft,



**Fig. 7.** Color change after industrial blanching operation (all samples were blanched in the same conditions, except for 'Carmel' that needed more temperature and time for an efficient peeling; using the same conditions, the peeling was not effective as for the other almond cultivars).

Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Xavier Miarnau:** Writing – review & editing, Visualization, Validation, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Michele Cutrone:** Writing – review & editing, Validation, Methodology, Data curation, Conceptualization. **Alejandro Calle:** Writing – review & editing, Validation, Data curation, Conceptualization. **Esther Sendra:** Writing – review & editing, Validation, Resources, Formal analysis, Conceptualization. **Ángel A. Carbonell-Barrachina:** Writing – review & editing, Validation, Software, Resources, Conceptualization. **Ignasi Batlle:** Writing – review & editing, Validation, Data curation, Conceptualization. **Agustí Romero:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Investigation, Conceptualization.

#### Declaration of competing interest

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

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.lwt.2025.117472>.

#### Data availability

Data will be made available on request.

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