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Factors influencing the almond kernel breakage during shelling processes and the impact of water conditioning on kernel color and free acidity

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ABSTRACT

Kernel breakage is the major economic challenge for the Spanish almond industry. Thus, this study aimed to determine the kernel breakage during the shelling operation by (ii) identifying the primary breakage factors, and (ii) evaluating the impact of water conditioning on final kernel quality. Twelve almond samples, of which 9 intraspecific hybrids were specially selected to enlarge the variability range. Kernel breakage ranged between 5 and 71%, with HYB8 registering the lowest breakage values and HYB5 the highest. Cultivars, 'Vairo', 'Guara', and 'Lauranne' showed also substantial breakage rates (40, 45, and 56 %). More absorbed water ($r = -0.71^{**}$), elasticity ($r = -0.60^{*}$), wider ($r = -0.70^{*}$) and rounder ($r = -0.65^{*}$) fruit with higher fat content ($r = -0.84^{***}$), reduced breakage in shelling operation. Meanwhile, almonds with a higher shell strength ($r = 0.63^{*}$), more elongated ($r = 0.67^{*}$), with higher skin ($r = 0.69^{*}$) and fiber content ($r = 0.58^{*}$) were more susceptible to breakage. Water conditioning produced a color change in kernel, while the oil acidity was similar before and after (0.1%) the conditioning process, meaning that, this was fast and correct enough to avoid enzymatic degradation. In the absence of significant technological advancements, further research must focus on optimizing water conditioning processes and standardizing cultivars to reduce kernel breakage in the Spanish almond industry.

1. Introduction

Almond is one of the most cultivated nut crops in Spain with a production of 370,727 t of shelled nuts and a harvested area of 744,000 ha in 2021 (increasing ~38% in the last 10 years) ((MAPA, Ministerio de Agricultura, Pesca y Alimentación, 2022)). One of the most significant advances in the almond crop sector was the release of two types of new cultivars (i) those characterized by a delayed blooming to avoid frost damages, and (ii) the self-compatible ones to avoid the use of costly pollinators and being able to maximize yield (Batlle et al., 2017). With the introduction of new almond cultivars and the subsequent increase in almond production, new postharvest handling practices must be adopted to avoid a decrease in the quality of the final products. Currently, one of the biggest challenges faced by the Spanish almond industry is the kernel breakage which can cost significant economic losses. Broken kernels reduce the quality grades of the commercial products and their market values, where only "whole" kernels are accepted. The highest almond quality grades in Spain are "extra", "supreme" and "selected", where the mechanically damaged nuts, halves and broken pieces accepted are 2, 5 or 10%, respectively (ALMENDRAVE, 2020).

Almonds undergo a series of impacts from harvest to the final product that might decrease the kernel resistance (Verdú et al., 2017). For instance, when almonds are ready to be harvested, different shaking machines are used to collect the fruits. Then, hulling machines are used to remove the hull from the shell; later, shelling machines are used to remove the shell from the kernel, and finally peeling machines are used to remove the skin from the kernel. Each one of these unit operations and the machinery used in them can produce significant mechanical damages in the kernel resulting finally in the breakage of the nuts.

Moreover, during postharvest farmers must keep the in-shell almonds dry; this is kernel moisture must be lower than 6%. This low moisture content will guarantee an appropriate control over aflatoxin

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production as almond processing has a low impact on aflatoxin reduction (Zivoli et al., 2014). For instance, despite blanching, a significant portion of aflatoxins persisted in the almond kernel, with 90–93% found in the peeled almond and the remaining 7–10% in the skin post-blanching (Zivoli et al., 2014). This highlights the challenge of reducing aflatoxin levels during almond processing. Thus, to prevent contamination, it's crucial to maintain a moisture content below 6% during initial drying and storage. However, this can make the kernels brittle, crunchy and susceptible to mechanical damage.

Thus, it is important that before conducting the shelling unit operation, a proper conditioning step must be done by soaking almonds in cold water and leaving them enough time to absorb enough water to (i) reduce shell strength and (ii) increase kernel deformation. This moistening process will significantly reduce kernel breakage by making kernels more capable of adsorbing the impact of the hammers during the shelling operation (Shirmohammadi et al., 2018; Shirmohammadi & Fielke, 2017).

The shelling process uses different systems according to the shell hardness. In Spain, hard shell almond cultivars are produced due to their good adaptation to rain-fed growing conditions, their resistance to birds/insects, and long shelf life (Socias i Company et al., 2017). For hard shell cultivars, Spanish shelling plants use a system consisting of knocking hammers or circular bars, of which 1 bar is fixed and the other mobile (Verdú et al., 2017). The mobile bar or hammer hit the almond when the almond goes through a hole and cracks it. On the other hand, processing plants transforming soft shell cultivars, mainly produced in USA and Australia, use a completely different shelling system, consisting of solid rubber rollers that revolve at different speeds and provide shearing forces to break the almond shell (Ledbetter, 2008). Both systems are configurated according to nut characteristics; thus, a deep knowledge on the physical and mechanical properties of all almond cultivars is of utmost importance to be able to minimize the damage of kernel during pre- and especially pos-harvest operations (Fornes Comas et al., 2019; Shirmohammadia & Charrault, 2018). Although there are not official statistics, different Spanish industries have reported kernel breakage ranging between 2 and 30% for the in-shelling operation, depending on year and cultivar.

There are two other important almond attributes that can be affected by the soaking step previously described, these are the color and free acidity. This unit operation is normally conducted in silos of approximately 60 t of capacity and moistened almonds can increase significantly their temperature and consequently color changes can be expected, which can later affect consumer satisfaction. Additionally, the overall almond stability and shelf life could be also compromised, and free acidity (expressed as percentage of oleic acid) may be a useful parameter to evaluate this impact (Martin-Tornero et al., 2024). Lower acidity values are recommended for good quality almonds, for instance the Spanish standards require maximum values of 0.7% of oleic acid for fresh and healthy almonds (DESCALMENDRA National Association of Almond Shellers of Spain, 2024). Similar to the case of extra virgin olive oil which accepts maximum values of 0.8% (Issaoui & Delgado, 2019). Exposure to high temperatures normally result in high values of acidity, as reported during almond roasting (Martin-Tornero et al., 2024); also long storage or inadequate storage conditions also result in higher acidity values.

Therefore, the present study aimed to assess for first time the kernel breakage during the shelling operation using the equipment normally used by Spanish almond industry. To achieve this aim, two specific objectives were established: (i) identifying the main factors controlling nut breakage, and (ii) evaluating the effect of the water conditioning step on the final kernel quality. To address these objectives, we hypothesized that (i) kernel breakage rate will vary significantly among different almond cultivars due to differences in shell properties and that (ii) water conditioning will have a positive impact on kernel elasticity and reduce kernel breakage, but its effectiveness will depend on the specific cultivar and its shell properties. By testing these hypotheses, we aim to gain a deeper understanding of the factors influencing kernel breakage during the shelling process and identify strategies to minimize losses and improve the quality of the final product.

2. Materials and methods

2.1. Pilot plant shelling operation

For the first experiment, 360 kg of in-shell almonds (10 kg × 12 samples × 3 repetitions) belonging to 12 almond samples were evaluated in terms of their resistance to the IRTA's pilot plant shelling machine and were physicochemically characterized to determine possible factors responsible for kernel breakage. The sample size was determined based on preliminary pilot plant trials and the capacity of the shelling machine. The samples consisted of 3 almond cultivars already commercialized and grown in Spain, 'Guara', 'Lauranne', and 'Vairo', complemented with 9 intraspecific hybrids needed to enlarge the variability range. All samples belonged to the experimental field of IRTA Mas Bové Research Station; NE Spain; 41° 10′ 16″ N, 1° 11′ 30″ E, under standard irrigation. Before shelling, 10 kg of in-shell almonds went through a conditioning process which consisted of soaking the almonds in cold water (17.1 °C ± 0.40 °C) during 1 min, draining during 3 min, and resting in closed plastic bags during 24h. These conditions were established according to the industry practices. All samples were processed in exactly the same conditions, seeking to simulate the industry process of almond cracking in Spain (Verdú et al., 2017) which includes the almond soaking before cracking to increase almond pliability and reduce the risk of breakage. After 24h of rest, samples were passed to the cracking machine (model 206, manufactured in 2008 by Borrell S.A. Denia, Alicante, Spain) composed of a feeding hopper, calibration system, hammer system, elevator, screening and aspiration system, manual sorting table, and control panel from where the entire shelling line was controlled. The calibration system guided the almond to the appropriate fitting diameter of the hammers system formed by groups of punched circular bars of different diameters. Each group consisted of one fixed and one mobile bar; so, when the almond reached the hole between bars, the mobile bar moved, pressed the almond against the fixed bar and cracked it. After cracking, the elevator carried the mixed whole almonds, shells and kernels to the screening and aspiration system where were separated by density and later manually.

The whole process was done in triplicate for each sample and the results of the kernel breakage were expressed in percentage. Kernels were dried back to values below 6% moisture content at 40 °C for 72h, ground and stored in vacuum bags in freezing condition until analyzed. Then they were analyzed to determine the moisture, fiber, protein, and fat content to detect possible factors responsible for kernel resistance.

2.2. Physical characteristics of almonds

2.2.1. Moisture content before and after water conditioning

Moisture was determined before and after almond conditioning process for dry and wet in-shell almonds and kernels to show the moisture content before and after conditioning process. Moreover, the moisture content of ground kernels obtained after the shelling and drying process was also determined to be able to express the proximate analysis results in dry weight. For the conditioning process, 10 in-shell almonds and 10 kernels for each shelling replication in duplicate were placed in a pre-weighted aluminum tray and oven dried (model DRY-BIG 2007341, SELECTA, Abrera, Barcelona, Spain) at 105 °C to constant weight. While for the ground almond, 1 g of sample was dried (MEMMERT UF55 D-91126 Schwabach GERMANY) at 103 °C for 4 h. After drying, the aluminum trays and porcelain cresols were directly cooled in a vacuum desiccator containing allochronic silica gel for 30 min. Wet basis moisture content was calculated based on almond weight before and after drying, using equation (1), and the results were expressed in % of wet basis.

$$Moisture\ (\%wb) = (Wi - Wf)/(Wi - W1) \times 100 \quad (1)$$

where *Wi* and *Wf* are weights of moisture trays with almond samples before (initial) and after (final) drying, respectively, while *W1* refers to the weight of empty aluminum tray.

2.2.2. Instrumental texture before and after water conditioning

The strength or maximum force required to break the samples and the extension was measured before and after conditioning process as previously described by Lipan et al. (2022) using an INSTRON texture analyzer model 3344 (Norwood, MA, USA) and a cylindrical probe of 8 mm diameter descending at 1 mm s^{-1}. Twenty-five in-shell almonds and other 25 kernels of each shelling replication (75 in-shell almonds and 75 kernels per sample) were measured before and after the conditioning process using a compression test until breakage.

2.2.3. Morphological parameters and physical properties

Some physical properties (weight, length, width, and thickness) were measured to determine the almond shape and size, and to understand if this can have a relationship with the kernel breakage. For the measurements a scale model AG204 Mettler Toledo (Barcelona, Spain) and a digital caliper (Mitutoyo 500-164-30, Kawasaki, Japan) were used. With these values, several geometric factors such as length to width ratio (L/W), geometric mean diameter (GMD), sphericity (∅), and surface area (S) were calculated using the following equations:

$$GMD\ (mm) = (Length \times Width \times Thickness)^{1/3} \quad (2)$$

$$\varnothing(\%) = GMD/Length \times 100 \quad (3)$$

$$S\ (cm^2) = \pi(GMD)^2 \times 10^{-2} \quad (4)$$

2.2.4. Kernel to shell ratio

The kernel to shell ratio was calculated based on the initial weight of the whole almonds and the resulted kernel. The weight of the kernel was divided by the initial weight of the whole almonds, and the result was multiplied by 100 to express the results in percentage.

2.2.5. Skin percentage determination after laboratory blanching operation

For almond blanching 100 g of almonds were poured into a laboratory beaker (500 mL capacity) filled with 300 mL of boiling water, and were kept for 1 min at 100 °C. Almonds were manually pilled, and dried in a stove for 12h at 70 °C. This process was carried out in triplicate and the skin was expressed as percentage of the total kernel weight. In this step, the kernel breakage percentage was also calculated.

2.3. Chemical composition of almond kernels

Protein, fat, and fiber content were determined in duplicate for each shelling replicate with a total of 6 values per each sample. Almond kernels (30 g) were ground using a grinder model KN 295 Knifetec FOSS (Hillerød, Denmark) in 2 cycles of 5 s each. The determinations were done following the methodology described by Lipan et al. (2022).

2.4. Color change in almonds after conditioning and blanching process

Color parameters were determined for the skin and inside kernel before and after conditioning process to understand the effect that water conditioning can have in kernel color. First L*, *a** and *b** color coordinates 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. Using the values of color coordinates of dry almonds before conditioning as reference, together with wet samples after the conditioning process and wet-back-dried samples, (after conditioning, shelling, and drying process) the color difference was calculated with the following equation (3):

$$\Delta E = \left((L - L^*)^2 + (a - a^*)^2 + (b - b^*)^2\right)^{1/2} \quad (5)$$

where, *L**, *a** and *b** represent the color coordinates values of dry almonds (before conditioning), and *L*, *a* and *b* represent the values of processed almonds.

2.5. Almond oil extraction and free acidity determination

The oil extraction procedure consisted of pressing the almonds at room temperature using a hydraulic press (LARZER model AC22014, Mallabia, Vizcaya, Spain) and the solid residue was then separated by centrifugation (SIGMA model 3-16k, Newtown Wem, Shropshire, United Kingdom) at 5.444×g for 10 min. The free acidity of almond oil was then determined by titration of 10 g of oil solution in 50 mL of ethanol:diethyl ether (1:1) previously neutralized with potassium hydroxide (KOH) 0.1M in presence of 1 mL of phenolphthalein as indicator. The solution with the sample was then titrated with KOH (0.1M) under stirring until color change. The volume (mL) of KOH needed was registered and used for the calculation. The results of free acidity were expressed as percentage of oleic acid since this was the predominant compound.

2.6. 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 check the significant differences among samples for the studied parameters. Moreover, an orthogonal contrast analysis, it was used to perform custom hypothesis tests between edging groups if needed; in this case the hypothesis tested was $L\beta = 0$. Additionally, Pearson's Correlation Coefficient was carried out to assess the relationship between kernel breakage and the significant parameters. Partial least squares regression (PLS) was used by extracting successive linear combinations of the predictors, seeking those that explain both response and predictor variation. These analyses helped to find possible parameters responsible for the kernel breakage. All analyses were run with SAS-Stat Software (V9.4. SAS Institute Inc., CA, USA).

3. Results and discussion

3.1. Kernel breakage in shelling operation

Kernel resistance to the shelling machine was evaluated for 12 almond cultivars/intraspecific hybrids with different characteristics and the results are presented in Fig. 1. As observed, all samples showed different behavior in terms of kernel breakage which ranged from 5 to 71% with HYB8 recording the lowest breakage values, while HYB5 was the highest. As seen, the inclusion of intraspecific hybrids in the experimental design significantly expanded the range of breakage. The cultivars already commercialized like 'Guara', 'Lauranne' and 'Vairo', registered quite high breakage values such as 45, 56, and 40%, respectively. To identify the factors causing these significant breakage differences among samples, a detailed physicochemical characterization was essential.

3.2. Moisture content and textural properties of studied almonds

According to the scientific literature, previous trials, and the Spanish shelling industry, the moisture content is essential to increase kernel deformation and avoid kernel breakage during cracking (Shirmohammadi et al., 2018; Shirmohammadi & Fielke, 2017; Verdú et al., 2017). In the present experiment, all samples were subjected to identical water conditioning to distinguish the effect of other factors on breakage rates, and the results are presented in Fig. 2. Fig. 2A, shows the results of moisture content before and after the conditioning of in-shell almonds, while Fig. 2B, shows the results for moisture content before

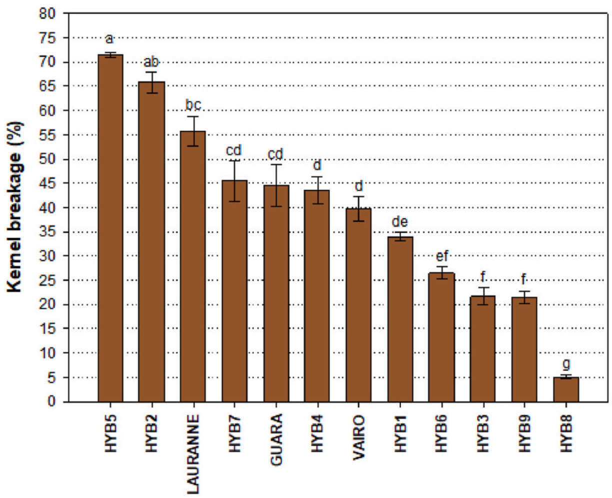

Fig. 1. Kernel breakage percentage in the pilot plant experiment (the conditioning process was the same for all samples regardless of their characteristics). Different letters indicate significant differences ($p < 0.05$) among samples according to Tukey's least significant difference test.

and after the conditioning process of kernels. Both graphs depict dry and wet almonds in red and blue, respectively. Post-conditioning, all almonds exhibited increased moisture content. Dry fruits showed relatively consistent moisture levels, while those wet displayed significant fluctuations. Moisture increments from dry to wet samples ranged from 3 to 20% in almonds and 1–9% in kernels, with HYB7 and HYB9 showing the lowest and HYB3 the highest increases.

Moreover, texture is another important parameter that might influence kernel breakage. Authors reported that shell characteristics make the shelling process less effective for hard shell almonds and can affect the percentage of undamaged kernel recovery if the cracking machines are not optimized according to each type of shell strength (Shirmohammadi & Fielke, 2017). Here, texture was expressed as breaking strength, defined as the maximum force required to cause breakage (N). The in-shell almond strength (Fig. 2C) was very different among samples and ranged from 131 to 805N, while in the kernel (Fig. 2D) from 86 to 126N. According to Romero et al. (2018), almonds with shell textures of 77, 165, 252, 537, and 718 N, correspond to the following categories: paper, soft, semi-hard, hard, and stone shell, respectively. Thus, HYB3 and HYB8 with texture values of 131 and 168 N could be considered soft shell almonds; HYB4 (271 N) and 'Lauranne' (248 N) semi-hard; HYB1 (340 N), HYB6 (355 N), HYB9 (363 N), and 'Vairo' (390 N) more closed to hard texture; HYB5 (548 N) and 'Guara' (511 N) hard shell; while HYB2 (740 N) and HYB7 (805 N) stone shell. Again, it can be observed that the inclusion of intraspecific hybrids in the study widened the observed texture range. Almond shell (endocarp) is a woody layer composed of cellulose, hemicellulose, and lignin, that encases and protects the almond kernel. According to the scientific literature, the soft shell might have a lower content of cellulose and lignin than hard-shell almonds. For instance, almond shells from California contained 23% of cellulose, 33% of hemicellulose, and 24% of lignin, while shells from Spain cv. 'Marcona', contained 37% of cellulose, 32% of hemicellulose, and 27% of lignin (Caballero et al., 1996; Gong et al., 2011; Vidal, 2020). However, other authors working with almond shell of different cultivars from Spain both soft (cv. 'Mollar') and hard (cv. 'Marcona', cv. 'Llargueta'), found equal content of these compounds and similar characteristics (García et al., 2020).

In the present study, the results suggested that the conditioning process reduced shell strength by approximately 44 N, based on the mean value across all cultivars and intraspecific hybrids (Fig. 2C). Although, for HYB3, HYB7, HYB8, and HYB9, the differences in shell strength were not significant. Considering the shell texture characteristics and moisture content it can be assumed that soft-shell cultivars (HYB3 and HYB8) absorbed the highest amount of water. Since their shells were already soft, the conditioning process did not significantly affect shell strength but increased kernel deformation. This was evidenced by higher kernel moisture content and a lower percentage of broken kernels after the shelling process. In contrast, hard-shell (HYB9) and stone-shell (HYB7) hybrids exhibited the lowest moisture content increments, which explains the consistent texture values observed before and after the water conditioning process. This result may be attributed not only to shell strength but also to factors such as shell structure and porosity; because, for instance, HYB7 was approximately twice as hard as HYB9. Despite this, both hybrids maintained their shell strength after the conditioning process, as they absorbed only small amounts of water, approximately 3%, compared to 9 and 20% for the soft-shell almonds. It is important to highlight that HYB9, despite showing the lowest moisture content increment and no change in shell strength after the conditioning process, exhibited the second-lowest kernel breakage rate (after HYB8). This breakage rate was even lower than that of other samples with greater moisture content increments. Therefore, factors other than moisture content and shell strength, such as almond morphology, may also play a role in kernel breakage.

Kernel texture was evaluated both before and after water conditioning, as well as after the blanching process in de-skinned kernels (Fig. 2D). As observed, the difference in strength between dry and wet kernels with skin was not as pronounced as for in-shell almonds. Most samples showed no significant change in kernel strength after the wetting process, except for HYB1 and HYB3, which exhibited a decrease in strength following wetting. The presence or absence of the skin significantly influenced kernel strength as kernel texture decreased by an average of 28 N once the skin was removed, highlighting the importance of the skin in maintaining kernel strength.

3.3. *Skin percentage and kernel breakage after laboratory blanching*

The skin has industrial importance because it influences almond texture, as previously discussed. Furthermore, its removal during the blanching process implies a weight loss, translated to a significant economic impact. The skin percentage (Fig. 2E) ranged from 4.4 to 7.2% which is in agreement with other authors that reported values between 4% (Lacivita et al., 2024) to 10% in almonds (Socias i Company et al., 2017). The cultivars/intraspecific hybrids with the lowest skin percentage were HYB8 and HYB9, whereas HYB5 (6.3%) and HYB2 had the highest percentages. Notably, the cultivars/hybrids with the highest skin percentages also registered the highest kernel breakage rates.

Kernel breakage after laboratory blanching values is represented in Fig. 2F, using boxplot graphics. Intraspecific hybrids HYB5, HYB2, and HYB7 showed the highest breakage, whereas HYB8, HYB6, and HYB1, had the lowest. Though the ANOVA resulted in a low significance level ($p = 0.1026$) regarding the effect of the varietal factor on kernel breakage in laboratory blanching, using an orthogonal contrast analysis, it was evidenced a significant difference ($p = 0.0021$) between the mean of the edging groups of hybrids HYB1 and HYB2 against HYB8. Blanching of almonds was carried out in the laboratory, whereas the blanching parameters could be standardized, the peeling operation was manual, thus, the force required to peel was not standardized and this explained the variability of the data among the 3 repetitions. However, the authors decided to show the present data because, although the differences had a low significance level, the broken kernel percentage, in general, followed the same trend as the kernel breakage after shelling (Fig. 1). It is important to highlight that this trend can change when blanching is run under industrial as compared to laboratory conditions, as the industrial practice involves multiple physical and thermal shocks, which can significantly affect the integrity of kernels. For this reason, the next step of the research is to peel these samples at the industrial level.

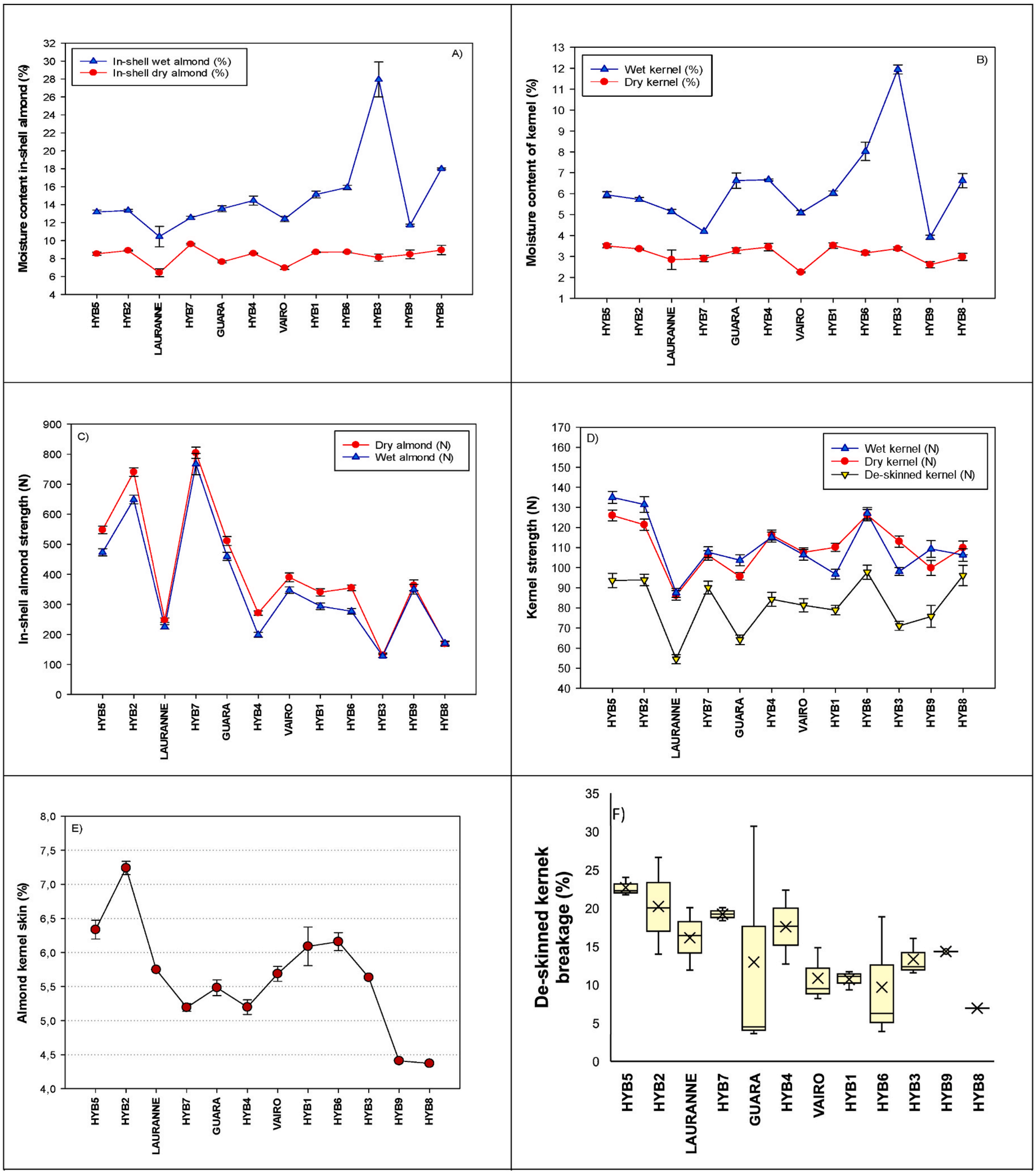

Fig. 2. Mean values of moisture and texture before (red color) and after (blue color) water conditioning for in-shell almonds (A, C) and kernel (B, D-dry kernel with skin in red, wet kernel with skin in blue, and dry de-skinned kernel in yellow). Almond skin (E) and broken kernels in blanching operation at laboratory level (F). Vertical bars are for standard deviation. Almond cultivars sorted from left to right in descending order of kernel breakage.

3.4. Morphological parameters and physical properties

To evaluate the physical properties of the in-shell almonds, the length/width ratio (L/W), sphericity, geometric mean diameter (GMD), and surface area were calculated based on length, width, and thickness of the almond and kernel (Table 1). Parameters such as L/W and sphericity provide information about the shape of the almond, essential for understanding its behavior during shelling. Geometric mean diameter and surface area provide information about the overall size of the almond and the available surface, crucial for processes such as water absorption and kernel breakage. The samples were different in morphological and physical characteristics, with length to width ratio (L/W) ranging from 1.1 to 1.8 and sphericity values ranging from 62 to 80%; higher values of L/W representing more elongated fruit, and higher values of sphericity represent more spherical or rounder fruit. Thus, samples with the highest values of L/W and lower values of sphericity (elongated fruit) were HYB2 (1.8; 62%), HYB5 (1.52; 69%), HYB6 (1.55; 67%) and HYB7 (1.55; 67%), whereas samples with the lowest values of L/W and highest sphericity (rounder fruit) were HYB9 (1.15; 80%), HYB8 (1.20; 78%), HYB4 (1.39; 72%). Moreover, 'Guara' (1.31; 75%) was the rounder one, followed by 'Vairo' (1.39; 71%), while 'Lauranne' (1.47; 68%) was more elongated. Regarding GMD and surface area, 'Lauranne' was the sample with the lowest values (17.9 mm and 10.2 cm^2) while HYB6 and HYB8 presented the highest values (24 mm; 18.8 cm^2; and 24 mm; 18.0 cm^2). These samples HYB6 and HYB8 with the highest surface area were also the sample with the highest

Table 1
Morphological parameters and physical properties of the in-shell almond and kernel.

	In-shell almond							Kernel							
	Length (mm)	Width (mm)	Thickness (mm)	Length/ Width (mm)	GMD (mm)	Sphericity (%)	Surface area (cm^2)	Weight (g)	Length (mm)	Width (mm)	Thickness (mm)	Length/ Width (mm)	GMD (mm)	Sphericity (%)	Surface area (cm^2)
ANOVA															
Test†	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***
Tukey Multiple Range Test‡															
HYB5	31.6c	20.8de	16cde	1.52bc	21.9de	69.4de	15.1de	1.22bc	23.3c	13.6b	8.58 ab	1.72bcd	13.9bc	59.8de	6.11bc
HYB2	36 ab	20.2e	15.3ef	1.78a	22.3cd	62.1g	15.7cd	1.28b	24.6b	13.7b	8.49 abc	1.8 ab	14.2bc	57.8ef	6.31b
LAURANNE	26.3f	17.9f	12.2h	1.47cd	17.9h	68.3ef	10.2h	0.75g	19.5e	11.1d	6.84f	1.76bc	11.4f	58.4e	4.09f
HYB7	34.2b	22.1cd	16.4bcd	1.55b	23.2bc	67.8ef	16.9bc	1.29b	25b	13.5b	8.13bc	1.86a	14bc	56f	6.16bc
GUARA	29.1de	22.2c	15.8de	1.31f	21.7 def	74.6b	14.8 def	1.01ef	21.9d	13.6b	7.96cd	1.63efg	13.3de	60.9cd	5.57de
HYB4	28.1e	20.3e	14.6 fg	1.39e	20.3g	72.1c	12.9g	1.05de	21d	12.9bc	8.55 abc	1.64defg	13.2de	62.9bc	5.51de
VAIRO	29.1de	21cde	14.3g	1.39e	20.6 fg	70.7cd	13.4 fg	1.09de	21.5d	13.3bc	7.23ef	1.62 fg	12.7e	59.3de	5.10e
HYB1	30cde	21.4cde	15.3ef	1.40de	21.4defg	71.5cd	14.4defg	0.92f	21.6d	12.7c	7.48de	1.71bcde	12.7e	58.8de	5.06e
HYB6	36.8a	23.8b	16.7bc	1.55b	24.4a	66.5f	18.8a	1.57a	26.5a	15.7a	8.56 abc	1.69cdef	15.2a	57.6ef	7.30a
HYB3	29.4de	20.4e	15.3ef	1.45cde	20.9efg	71.1cd	13.8efg	1.06de	21.3d	13.5bc	8.74a	1.59g	13.6cd	63.8b	5.80cd
HYB9	29de	25.2 ab	17.1 ab	1.15g	23.2bc	80a	16.9bc	1.15cd	20.8d	15.4a	8.95a	1.36h	14.2b	68.2a	6.33b
HYB8	30.6cd	25.4a	17.6a	1.20g	23.9 ab	78.2a	18.0 ab	1.25bc	20.9d	15.5a	8.77a	1.35h	14.1bc	67.7a	6.31b

†***, significant at $p < 0.001$, respectively. ‡Values (mean of 75 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.

moisture increment and with the lowest kernel breakage. Authors reported similar ranges of values for these parameters in almonds. For example, Pérez-Sánchez and Morales-Corts (2021) worked with 24 traditional cultivars grown in the central-western Iberian Peninsula and reported a range of sphericity from 60% to 79% with cv. 'Cornicabra' being the least round and cv. 'Marcona' being the most round. For GMD reported values ranging between 18.8 mm (cv. 'Bravía') and 34.7 mm (cv. 'Gorda José'), while for the surface area the values ranged between 11.2 cm^2 and 38.0 cm^2 for the same cultivars. Regarding 'Desmayo Llargueta' (elongated) and 'Marcona' (round), authors reported the following values: sphericity 62% and 79%, GMD 22 mm and 25 mm, and surface area 15 cm^2 and 19 cm^2. Considering these values, HYB2 is the sample more like 'Desmayo Llargueta', while HYB8 and HYB9 were more similar to 'Marcona'.

3.5. *Factors responsible for kernel breakage in shelling operation*

Pearson's correlation coefficient (r) was used to determine physicochemical parameters responsible for kernel breakage in pilot plant shelling operation. All significant parameters were used; however, for morphological parameters as the correlation between nut and kernel was significant (length $r = 0.95$***; width $r = -0.87$***; thickness $r = -0.63$*; and length to width ratio $r = 0.80$**), only data from in-shell almond were used. Nine parameters were found to be correlated with kernel breakage (Fig. 3) of which 5 were negatively correlated and 4 positively correlated. Negative and significant correlations were found between kernel breakage and (i) absorbed water (Fig. 3A; $r = -0.71$**); (ii) kernel deformation (Fig. 3B; $r = -0.60$*); (iii) width (Fig. 3C; $r = -0.70$*); (iv) sphericity (Fig. 3D; $r = -0.65$*); and (v) fat content (Fig. 3E; $r = -0.84$***). In other words, more absorbed water, more elasticity, and wider and rounder fruit with higher fat content seem to reduce kernel breakage. On the other hand, positive and significant correlations were found between kernel breakage and (i) almond strength (Fig. 3F; $r = 0.63$*); (ii) length-to-width relation (Fig. 3G; $r = 0.67$*); skin percentage (Fig. 3H; $r = 0.69$*); and fiber content (Fig. 3I; $r = 0.58$*). This means that almonds with higher shell strength, more elongated, higher percentage of skin, and higher content of fiber seemed to be more susceptible to breakage. Besides the direct correlation between kernel breakage and the mentioned parameters, interesting correlations among the other parameters were found. For instance, kernel to nut ratio was negatively correlated with shell strength (Fig. 3J; $r = -0.75$**) and positively correlated with the moisture increment (Fig. 3K; $r = 0.65$*). This statement highlights that almond cultivars with a higher kernel to shell ratio are usually almonds with a softer shell that permits easier water penetration and assures a lower percentage of kernel breakage in shelling operation. This claim is also supported by other authors who worked with (i) 167 seedlings from the cross 'R100' (selection of INRA) × 'Desmayo Largueta' (traditional Spanish cultivar) (Sánchez-Pérez et al., 2007) cultivated in CEBAS-CSIC, Murcia, Spain and (ii) with 400 samples of almonds belonging to different cultivars such as 'Mission', 'Monterey', 'Padre', 'Ruby', 'Tarragona', 'Tuono', and two accessions, growth in California, USA (Ledbetter, 2008). Both works reported a negative correlation between kernel-to-nut ratio and shell hardness ($r = -0.84$** and 0.81**, respectively) even higher than the present results. It appears that with an increasing proportion of almond shell material, the shell becomes more difficult to crack, and the impact of hammers might be higher. However, Ledbetter (2008) also showed that not all the cultivars behave in the same way, as seen in the present study. For instance, HYB8 registered the same kernel ratio as 'Vairo', and the shell hardness was different, the former was soft shell (168 N) and the latter was categorized as more hard shell almond (390 N). This means that also other aspects such as morphology, geometrical properties, shell composition or shell structure are responsible for kernel damage in this operation. Therefore, characterizing each cultivar and optimizing the process accordingly is essential before starting the shelling process.

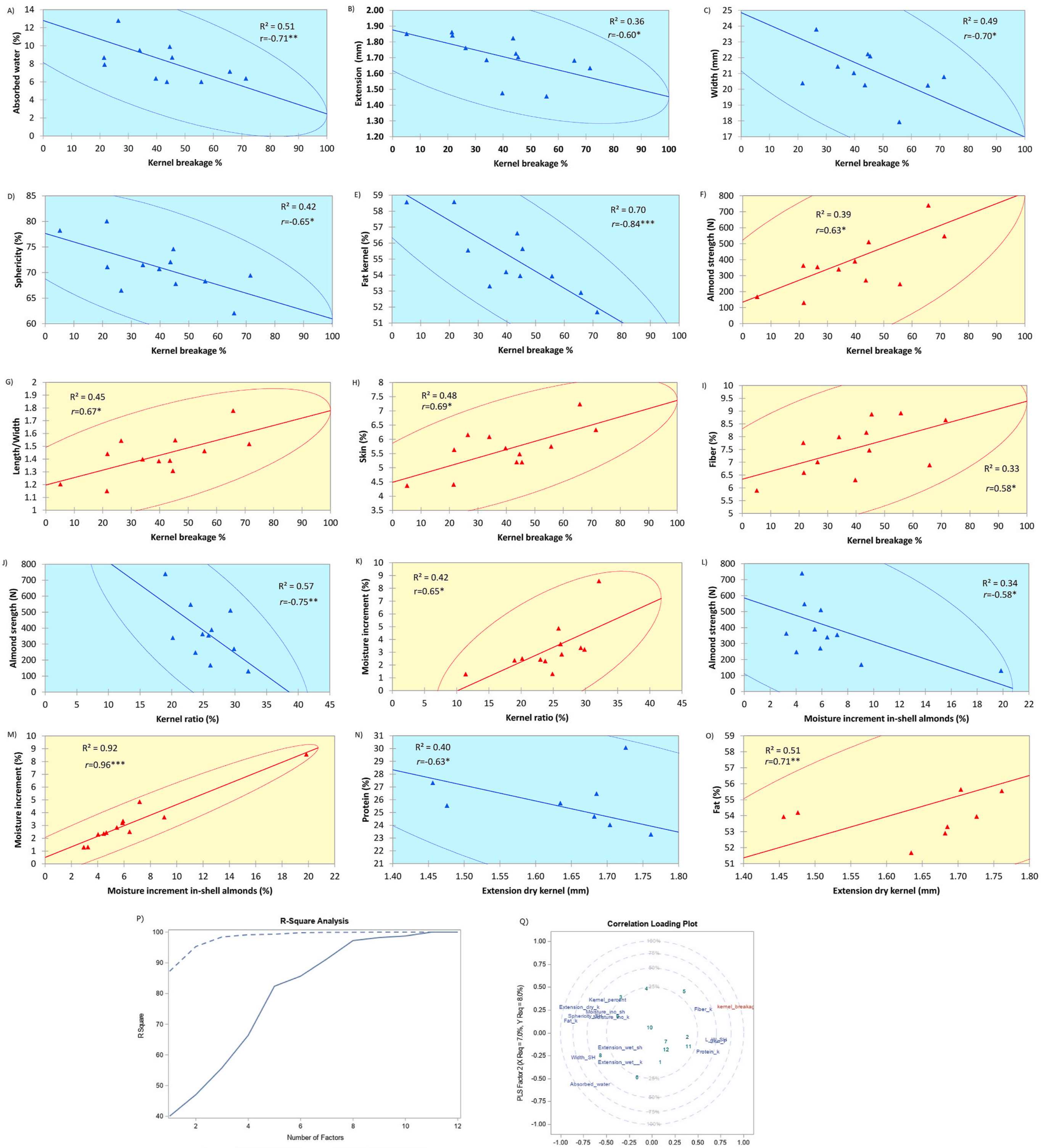

Fig. 3. Pearson's correlation coefficient (r) among Kernel Breakage percentage in shelling operation and A) Absorbed water; B) Extension; C) Width; D) Sphericity; E) Fat kernel; F) In-shell almond strength; G) Length/width ratio; H) skin %; and I) Fiber. Correlations between (i) Kernel to nut ratio with J) Almond strength and K) Moisture increment in kernel; (ii) Moisture increment in almond with L) Almond strength and M) Moisture increment in kernel; (iii) Kernel extension with N) protein and O) fat. Partial least Square regression: P) Graphical depiction of the R-square analysis, and Q) correlation loading plot.

Another negative and important correlation was found between moisture content increment and shell hardness (Fig. 3L; $r = -0.58^*$) as well as moisture increment of in-shell almonds with moisture increment of kernels (Fig. 3M; $r = 0.96^{***}$). Considering that a lower shell strength and a higher absorption of water help to reduce kernel breakage, a strong consideration is that the conditioning process of almonds is one of the most important steps to be optimized. This claim can be explained by the example of these two-almond hybrids HYB8 and HYB9. The kernel breakage percentage was 5% and 20% for each one, a big difference between them. However, HYB9 registered one of the lowest percentages of broken kernel after HYB8, and one of the reasons might be the sphericity of the sample. Because as observed in Pearson's correlations more spherical samples are related to less damage in the kernel. This statement could be associated with the fact that the hammer system of the present shelling machine was composed of circular bars (Fig. 1S). The present shelling system and in general the Spanish shelling industry were at the beginning manufactured for cv. 'Marcona', which is a round almond with a sphericity of 79% (Pérez-Sánchez & Morales-Corts, 2021). If the sphericity between HYB8 and HYB9 is compared, similar results can be found (78 and 80%, respectively). In this case, the differences between these samples consisted of shell texture which was very different (soft and hard, respectively). This difference in shell texture hindered uniform water absorption, with HYB9 being more affected due to its harder shell texture. Due to the similar conditioning process across samples, and the heterogeneity of each cultivar's characteristics, the kernel damage was very different among samples. Thus, understanding the typology of each cultivar is crucial to optimize the conditioning process to achieve adequate moisture levels before cracking. This approach could significantly reduce the kernel damage in shelling operation, potentially achieving consistent results for these two cultivar/hybrids regardless of their initial characteristic. Last but not least, the moisture content level must be also established for each cultivar because the present study showed that samples with values of 7% recorded lower kernel breakage (5%) than other samples with 12% of moisture content (21%) because other aspects such as shape, size and shell hardness influence the breakage. Authors reported lower shell hardness for smaller almonds (Khazaei, 2008).

Kernel extension or deformation increased with the moisture content, and this helped to absorb the hammer impact and reduce the kernel damage, resulting in agreement with other authors (Shirmohammadia & Charrault, 2018). Besides, negative, and positive correlations were found between the kernel extension with protein, and fat content, respectively. Higher protein reduced the kernel extension (Fig. 3N; $r = -0.63^{*}$) while higher fat increased it (Fig. 3O; $r = 0.71^{**}$). This backs up the hypothesis that fat content might increase kernel deformation and help to reduce kernel breakage in shelling operations. This statement was not previously reported in almonds. Usually, moisture content is the parameter that influences the deformation status of almonds the most. However, the scientific literature reported that in the absence of fat, solids exhibit more brittleness (Bourouis et al., 2023), which is consistent with the texture observed in the dry almond kernel. When kernels are dry the kernel response under loading (either the load cell in texture measurements or hammer impact in the shelling process) is more brittle which makes the almonds more susceptible to breakage, whereas a wetted kernel presents a more ductile-like behavior (Shirmohammadia & Charrault, 2018).

The graphical depiction of the R-square analysis (Fig. 3P) as well as a correlation loading plot (Fig. 3Q) summarizes the model based on the first two PLS factors. The proportion of variation explained (or R square) makes it clear that there is a plateau in the response variation after three factors are included in the model (width, L/W, and sphericity). Regarding the predictor variables, the first five factors included (width, L/W, sphericity, absorbed water, and extension) account for more than 80% of their variability. The dependent variable kernel breakage is well explained by the model since it is near the 100% circle. Projecting the variables' points onto the line that runs through the kernel breakage point and the origin, it can be observed that: (i) water absorption is the most determinant factor for kernel breakage, though in the negative direction; (ii) all the "extension" properties (from the wet shell, wet kernel, and dry kernel) reduce the kernel breakage as well. The extension observed during the texture assay is very related to water absorption; regarding the dry-kernel extension this could be a useful tool to assess the risk of breakage in raw almonds; (iii) the width and sphericity relate negatively with kernel breakage, whereas length to width ratio relates positively with it. These relationships could be explained because the machine was developed at first for round-shaped almonds. Regarding the kernel composition, the fat content seems to be the most important and it reduces the risk of breakage, whereas fiber content promotes the breakage risk, may be because fiber conforms the cell walls of the inner tissue of the kernel. The results of chemical composition can be visualized in Fig. 2S.

3.6. Effect of conditioning process on kernel skin and seed color

Although the color is not related to the kernel breakage, it is an important parameter both for the natural market (sold in skin) and for snack, milk, flour, and other almond-based products that require deskinned almonds. As previously explained, to reduce the kernel breakage, almonds must undergo a conditioning process which consists of wetting the almonds, resting around 24h, shelling, and drying back to 6% moisture content to assure the safety of the product. Due to the multiple thermal shocks involved in this process, it has been decided to measure both the skin (outer surface of the kernel) and the internal color of the white kernel to assess any changes resulting from these fluctuations. The results of color change from dry to wet kernels are presented in blue line, while the results of color change from dry to wet-back-dried kernels are marked in red color. The results for the kernel skin color change are presented in Fig. 4A, while those for the inner white kernel are shown in Fig. 4B.

Color changes were observed both in the skin and internal kernel compared to the reference dry kernels. In general, the color change in wetted almonds was higher than in wet-back-dried almonds, particularly for the inner kernel, with significant differences in almost all cultivars/hybrids. This is an expected behavior due to the water interactions, that reduces reflection and enhances transmission (Pillinger et al., 2023), making the product appearance darker. However, as previously mentioned, this is not the almond format usually commercialized.

The most important information is highlighted in red, indicating the color change from the initial kernel color after undergoing the entire shelling operations, which includes wetting, resting, and drying back to 6%. As seen, this color change was not as high as in wet samples. The color change in the wet kernel skin ranged from 2.3 to 6.7 with mean values of 3.8. The lowest color changes were registered by HYB2, HYB7, and HYB8, followed by HYB4, 'Vairo', 'Lauranne', and 'Guara'. The highest color changes were observed in HYB3 and HYB9. After the drying process, the color change in wet-back-dried kernel skin ranged from 2.0 to 4.8, with a mean value of 3.0. Hybrids HYB5 and HYB6, followed by HYB2, HYB8, HYB9 and 'Vairo' experienced the lowest changes, while HYB4, HYB3, HYB7, 'Guara', and 'Lauranne' showed the highest.

Regarding the inner kernel, color changes in wet almonds were even higher than in the skin, ranging from 1.9 (HYB7 and HYB8) to 15.2 (HYB1, followed by HYB3, and HYB6) and a mean value of 7.1. After drying, which is the way how industry commercializes the almonds, the inner color changes were lower, ranging from 1.5 to 7.5, and a mean value of 3.9, similar to the wet-back-dried skin kernel. The lowest changes were observed in 'Guara' followed by HYB5, HYB6, HYB7 and HYB8.

In wet almond samples, higher color changes were generally associated with higher moisture increment. However, in wet-back-dried almonds, the skin color change did not always correlate with the inner kernel color change for the same sample. For example, HYB9 showed the highest change in skin color but the lowest in the white kernel, with similar patterns observed for HYB1 and HYB4. On the contrary, some hybrids and cultivars exhibited consistent behavior in both the skin and white kernel, such as HYB5, HYB6, and 'Vairo.' A correlation analysis between the moisture content of wet and wet-back-dried samples revealed no significant relationship, suggesting that other compounds involved in color generation played a role in these changes.

3.7. Effect of conditioning process on kernel oil free acidity

Fig. 4C summarizes the free acidity results in almond cultivars and

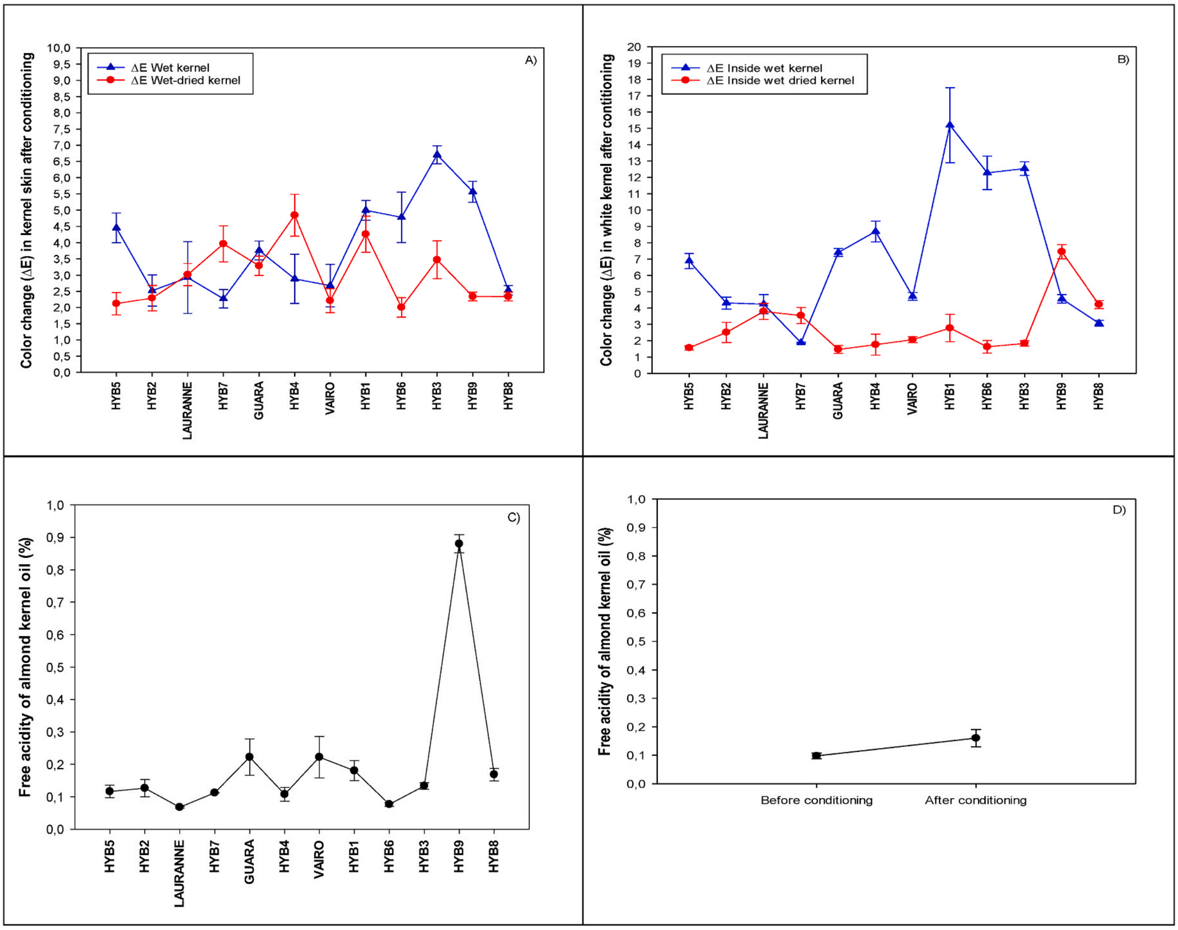

Fig. 4. Color change: A) in kernel skin (outside color) and B) in seed (inside color) after conditioning process; C) Free acidity of almond oil of all samples and D) before and after the conditioning process. Vertical bars are for standard deviation. Almond cultivars sorted from left to right in descending order of kernel breakage.

intraspecific hybrids and the conditioning effect on kernel oil free acidity (Fig. 4D). These values ranged from 0.07 to 0.78%, with HYB6 and 'Lauranne' having the lowest and HYB9, 'Guara,' and 'Vairo' the highest free acidity values. The rest of the samples showed similar values between them. These values were in agreement with other authors (0.64%) for the raw almond oil, which increased with the roasting process (1.34%) (Martin-Tornero et al., 2024). Moreover, it was consistent with those recommended by Codex Alimentarius, which requires free acidity values for unrefined oils below 5%. Most of the samples registered similar results of free acidity, and although there were 3 samples with higher values, were within the standards established by the Spanish industry and international authorities for extra virgin olive oil. This explains the freshness of the samples (2023 harvest). While conditioning (Fig. 4D) tended to increase free acidity in almond oils, the differences were not statistically significant. This means that almond conditioning caused no modifications on kernel quality. Authors reported that lipid deterioration occurs by enzyme-catalyzed hydrolytic cleavage or atmospheric oxygen-driven oxidative lipid cleavage (Lin et al., 2012). The first occurs when the moisture content is elevated above the critical level and causes an increase of the free acidity level. However, in the present research the conditioning was followed by drying that reduced the moisture content back to below 6%. Authors reported a lower level of free acidity in blanched kernels and attributed it to the lower lipase activity caused by the blanching process (Lin et al., 2012). To sum up, it is important to highlight that the increased moisture content due to water conditioning was not as high as it happens in the industry, and this moisture was dried back after the shelling process. Moreover, it is essential to remind that the experiment was carried out in a pilot plant in which 10 kg of almonds were soaked and stored in closed plastic bags to simulate the silos. However, the industry can easily work with more the 50 t of almonds at once (depending on each company) which are wetted and stored in closed silos. Thus, the physicochemical changes that can occur in industrial settings are of utmost importance to study and check if these results apply to those conditions.

4. Conclusions

The present research addresses a recently main issue of the Spanish almond industry in need to reduce the economic losses derived from kernel breakage. Thus, this is the first research that is meant to understand the conditioning process and shelling operation in the almond Spanish industry and their effect on kernel breakage and quality. For the 12 cultivars and intraspecific hybrids assessed within the present study, the kernel breakage ranged from 5 to 71%. While 5% breakage values are typical, higher percentages are a problem for the shelling industry. Therefore, it is important to emphasize that this study was carried out in a pilot plant in which standardized water conditioning was intentionally applied to all samples to assess their performance under uniform conditions. The significant deviation observed among them, calls attention to the need to adapt the conditioning and shelling methods to each cultivar, considering their unique physical, chemical, and structural characteristics, to minimize the kernel breakage. This means that is not correct to apply the same conditioning process to all the cultivars but to optimize it according to the characteristics of each one. The present results showed the heterogeneity among these 12 cultivars in terms of physicochemical properties which have a direct relationship with kernel breakage. Also, it highlighted that water conditioning allows to diminish considerably the breakage percentage, and this process changes significantly depending on the cultivar characteristics. Fruit shape was another important parameter that influenced kernel breakage in Spanish shelling machines because rounder fruits produced less breakage. Moreover, water conditioning, affected the kernel color, although, in wet-back-dried almonds, the color change was minimal. The free acidity of the oil kernel was not affected by the water conditioning process. Further research is needed to carry out this evaluation directly in industry shelling, blanching, and peeling machines and establish the kernel breakage after each step. As well as to optimize the water conditioning process of each cultivar before the almond cracking.

CRediT authorship contribution statement

Leontina Lipan: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Xavier Miarnau:** Writing – review & editing, Visualization, Validation, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Alejandro Calle:** Writing – review & editing, Validation, Methodology, Data curation, Conceptualization. **Ángel Carbonell:** Writing – review & editing, Validation, Software, Resources, Conceptualization. **Esther Sendra:** Writing – review & editing, Validation, Resources, Formal analysis, 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.2024.117250.

Data availability

Data will be made available on request.

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