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ORIGINAL ARTICLE

Fruit Gravimetrical Traits in Almond [*Prunus dulcis* (Mill.) D.A. Webb]: Combined Effects of Genetic Control and Environmental Drivers

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Abstract

Cultivated almond is an important nut crop commercially grown worldwide. The majority of research works carried out on almond fruit has been focused on chemical composition. However, fruit quality is defined by both chemical and physical characteristics, which are still not well documented. Here, we investigated gravimetrical traits of almond fruit in the five following cultivars: 'Ferraduel', 'Ferragnès', 'Fournat de Brezénaud', 'Marcona', and 'Tuono'. The present study was carried out across three different sites in northern Morocco namely Aknoul, Bni Hadifa and Tahar Souk and over two harvest seasons (2015 and 2016). Gravimetrical measurements consisted in: In-hull weight, nut weight, kernel weight, hull percentage, shelling percentage, true density, bulk density, and porosity. The outcomes of ANOVA demonstrated that cultivar, site, harvest season, and their interactions affected significantly almost gravimetrical traits. In fact, hull percentage, kernel bulk density, and both nut true and bulk densities were mainly under genotypic dependency, while harvest season (climatic factor) was the main variability source in kernel weight. Furthermore, site (edaphic factor) was the most important in determining in-hull weight, nut weight, and kernel true density, while shelling percentage, and kernel and nut porosities were controlled jointly by genetic and edaphic factors. Wide variabilities were found between cultivars, sites, and harvest seasons for almost parameters as demonstrated by LSD's test. Almond kernels from our cultivars were very small (cv. 'Tuono'), small (cvs. 'Ferraduel', 'Ferragnès', and 'Marcona'), and medium (cv. 'Fournat de Brézenaud'). Furthermore, corresponding nuts were hard (cvs. 'Fournat d Brézenaud' and 'Tuono') to very hard shelled (cvs. 'Ferraduel', 'Ferragnès', and 'Marcona'). Among sites, fruits harvested from Bni Hadifa performed better in terms of in-hull weight, nut weight, and kernel weight. Whereas, Tahar Souk had the greatest values of hull percentage and shelling percentage. Principal component analysis (PCA) allowed a good discrimination of cultivars, sites, and harvest seasons. The first component was of genetic order along which cultivars were separated, while the second and the third components exerted together an environmental control since they separated sites and harvest seasons, respectively. Significant correlations were highlighted among studied characteristics. The most important ones were modeled through simple regressions and therefore they can be used to predict each other.

Keywords Almond · Commercial cultivars · Gravimetrical traits · Genotypic effect · Environmental drivers

Gravimetrische Fruchteigenschaften bei Mandeln [*Prunus dulcis* (Mill.) D.A. Webb]: Zusammenwirken von genetischer Kontrolle und Umweltfaktoren

Schlüsselwörter Mandel · Handelsfähige Kultursorten · Gravimetrische Eigenschaften · Genotypischer Einfluss · Umweltfaktoren

Figs. 2–4 are related to PCA plots, while the 4th figure corresponding to linear relationships between some gravimetrical traits. These figures were designed using STATGRAPHICS program version XVII and Microsoft Office Powerpoint.

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Introduction

The almond tree [*Prunus dulcis* (Mill.) D.A. Webb] is originated from one or more wild plant species from deserts and mountains of central and western Asia. From this center of origin, almond has been widespread (Ladizinsky 1999). Cultivated almonds are important nut crops commercially grown throughout the world. Morocco is ranked as the fourth producer with 112,681 t of unshelled almonds (FAOSTAT 2016). This production fluctuates considerably from year-to-year due to many climatic occurrences, mainly frosts and droughts. Several commercial cultivars are found in the Moroccan orchards, but the most important in terms of cultivated acreage are: Cvs. 'Ferraduel', 'Ferragnès', 'Fournat de Brézenaud', 'Marcona', and 'Tuono'. The last three cultivars showed some chilling tolerance when cultivated in zones with frost risks (Sakar et al. 2017a).

From a pomological point of view, Esfahlan et al. (2010) reported that almond fruit can be divided into three portions: The kernel which is the edible part with a high nutritional value, while shells and hulls are used as livestock feed and burned as fuel. Hulls and shells are almond by-products generated during crushing process with amounts of more than 50% by fruit dry weight as pointed out by Moosavi-Dolatabadi et al. (2015). After harvesting, almond fruits undergo several postharvest handlings and processes: Dehulling, shelling, cleaning, separating, packing, sorting, storing, aeration, and transportation (Mohsenin 1970). For optimizing these post-harvest handlings, gravimetrical properties must be known. In the literature, many studies have been conducted to investigate fruit gravimetrical properties with respect to moisture content level (Aydin 2003; Razavi et al. 2007), effects of water regime, type of fertilizer, and harvest year (Valverde et al. 2006), and cultivated area (Rharrabti and Sakar 2016).

To the best of our knowledge, there is a scarcity of information about gravimetrical properties in almond cultivars grown commercially in Morocco. Therefore, the main objectives of this work were: (i) to characterize gravimetrical properties in the widely grown almond cultivars of northern Morocco, and (ii) to determine, to what extent, environmental factors could affect those properties.

Materials and Methods

Study Sites

Northern Morocco, known to host about the one-fifth of the cultivated almond area nationwide. The present study was undertaken in three different sites located in northern Morocco, namely Aknoul (60 km from Taza, 34°39′0″ N, 3°52′0″ W), Bni Hadifa (50 km from Al Hoceima, 35°1′22″ N, 4°8′27″ W), and Tahar Souk (50 km from Taounate, 35°1′22″ N, 4°8′27″ W). These sites were chosen on the basis of their important almond cultivated area, commercial production, and agronomical management practiced by local growers. In these three sites, orchards were conducted under rainfed conditions and underwent similar agronomical practices (without fertilizers). Bni Hadifa, is under coastal influence, while Aknoul and Tahar Souk, both semi-continental to Mediterranean influence. In 2015, which was a rainy year as compared to 2016, Bni Hadifa received 513 mm of precipitation with a mean annual temperature of 18 °C, but only 396 mm and 23 °C in 2016. The same trends were recorded in the two others sites, Aknoul and Tahar Souk had an annual rainfall of 484 and 473 mm with a temperature average of 14 and 14.3 °C, respectively in 2015, however, in 2016 they received only 290 and 267 mm as annual rainfall with an average temperature of 19 and 21 °C, respectively.

Plant Material and Sampling

The five widely grown almond cultivars were involved in this study were: Cvs. 'Ferraduel', 'Ferragnès', 'Fournat de Brézenaud', 'Marcona', and 'Tuono'. In each of the three sites and for all cultivars, three healthy and similar trees were tagged and used as replicates. At physiological maturity stage, which fits 89 on the BBCH (Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie) phenological scale, we harvested about 1.5 kg of fruits around the canopy from each of all marked trees across the three sites during two consecutive harvest seasons (2015 and 2016).

Gravimetrical Properties Measurement

Firstly, once at the laboratory, all impurities were removed from samples such as immature or broken fruits, as well as dust and dirty. From each sample, sub-samples of 30 fruits (Sorkheh et al. 2010) were considered for fruit weight measurements as follows: in-hull weight (HW) was obtained by weighing whole fruit with mesocarp using a precision electronic balance with a sensitivity of 0.001g. Following the method given by Zheng and Fielke (2014), the mesocarps (hulls) were removed manually to get nuts, which were weighted (nut weight, NW). Finally the nuts were cracked and the kernels were separated from the shell and weighted (kernel weight, KW). The whole gravimetrical traits investigated, their definition, abbreviation, and units are listed in Table 1.

Table 1 Nomenclature of fruit gravimetrical traits, abbreviations, and units

Gravimetrical trait	Unit	Abbreviation
In-hull weight	g	HW
Nut weight	g	NW
Kernel weight	g	KW
Hull percentage	%	HP
Shelling percentage	%	SP
Nut bulk density	Kg m^{-3}	$N\rho_b$
Nut true density	Kg m^{-3}	$N\rho_t$
Kernel bulk density	Kg m^{-3}	$K\rho_b$
Kernel true density	Kg m^{-3}	$K\rho_t$
Nut porosity	%	$N\varepsilon$
Kernel porosity	%	$K\varepsilon$

Hull percentage (HP) was calculated in % following the equation given by Ledbetter and Sisterson (2010)

$$HP = (\text{hull weight}/HW) \times 100$$

Where, hull weight = HW – NW.

Shelling percentage (SP) was computed as the ratio of kernel weight by nut weight following Kodad et al. (2015):

$$SP = (KW/NW) \times 100$$

According to Aydin (2003), the true density (ρ_t) of a fruit is defined as the ratio of the mass of a sample of a fruit to the solid volume occupied by this sample. Following Razavi et al. (2007), the liquid displacement method was used to determine volume of almond nut and kernel and their true density. In this assay, we used toluene (C_7H_8) instead of water because it is less absorbed by fruits. True densities in nuts and kernels were computed following the equation:

$$\rho_t = M_f/V_f$$

Where, M_f represents mass of fruit and V_f represents volume of fruit (volume of toluene displaced).

Bulk densities (ρ_b) of nuts and their kernels were achieved using a calibrated cylinder filled with a sample of nuts or kernels to the top surface and then the top was leveled (Dehspande et al. 1993). No compaction of nuts or kernels was done. Bulk and true densities values were calculated using the following equation: (in kg m^{-3}).

$$\rho_b = M_f/V_b$$

Where, M_f represents mass of fruit in a known volume; V_b represents volume of the cylinder.

Nuts and kernels porosities (expressed in %) were computed from the values of true density and bulk density using the following equation given by Mohsenin (1970):

$$\varepsilon = (1 - \rho_b/\rho_t) \times 100$$

Where ρ_b and ρ_t are the bulk and true densities respectively.

Statistical Analysis

All measurements and determinations were done at least in triplicate. The data obtained were subjected to statistical analysis by means of STATGRAPHICS package version XVII (Statpoint Technologies, Inc., Virginia, USA). Analyses of variance were computed using the general linear model procedure. Mean comparisons between sites, cultivars, and seasons were performed using the Least Significant Difference (LSD) test at a probability level of 5%. Principal component analysis (PCA) was performed on mean values to discriminate among sites, cultivars, and seasons. Correlation matrix was also calculated using mean values and some important relationships were plotted.

Results

Analyses of Variance

The outcomes of the combined analysis of variance for the whole investigated parameters are given in Table 2. It has been demonstrated that harvest season, site, cultivar, and their interactions affected significantly the majority of traits investigated. Moreover, cultivar effect was more important in determining hull percentage, nut true density, nut bulk density, and kernel bulk density since it explained around 57% of the total variance for these traits. Site effects allowed explaining more than 50% of the total variance for in-hull weight, nut weight, and kernel true density. About 67% of the total variation of kernel weight could be assigned to harvest season effect. Shelling percentage, nut porosity, and kernel porosity were controlled equally by genotypic and edaphic (site) factors. Cultivar, site, harvest season interactions were generally of lesser extent. Among these interactions, the most important was site × cultivar allowed explaining around 11% of the variability, while the remaining interactions together explained only 9%.

Mean Comparison Between Cultivars

Mean values of gravimetrical properties for each cultivar are shown in Table 3. LSD's test revealed wide variabilities between cultivars as regards to their gravimetrical prop-

Table 2 Mean squares of the combined analyses of variance for in-hull weight (HW), nut weight (NW), kernel weight (KW), hull percentage (HP), shelling percentage (SP), nut true density ($N\rho_t$), kernel true density ($K\rho_t$), nut bulk density ($N\rho_b$), kernel bulk density ($K\rho_b$), nut porosity (N_ε), and kernel porosity (K_ε) of five almond cultivars grown in different environments of northern Morocco (Aknoul, Bni Hadifa, and Tahar Souk) during two harvest seasons (2015 and 2016)

Source	Df	HW	NW	KW	HP	SP	$N\rho_t$	$K\rho_t$	$N\rho_b$	$K\rho_b$	N_ε	K_ε
Harvest Season (HS)	1	5.37***	4.64***	1.189***	205.9***	76.1**	9271.4***	987.7***	15,986.0	3.2	148.5*	4.6**
Site (S)	2	20.67***	17.65***	0.208***	492.4***	734.9***	48,204.1***	15,754.7***	449.4	2157.1***	337.3*	120.5***
Cultivar (C)	4	10.26***	9.59***	0.227***	1142.0***	888.4***	181,015.0***	7403.0***	79,845.3**	6216.3***	369.5**	162.9***
Replicate (Site)	6	0.11	0.06	0.008	8.4	5.8	244.9*	162.6	16,617.0	51.5	352.6*	0.5
HS × S	2	0.03	0.07	0.068***	25.6*	131.4***	7448.6***	1.5	15,801.2	0.1	448.3**	0.1
HS × C	4	0.01	0.03	0.005	13.8	16.5	3298.5***	1.5	15,797.9	0.1	359.8	0.1
S × C	8	3.02***	2.38***	0.054***	302.7***	197.8***	13,438.9***	7099.1***	28,861.0*	653.7***	500.3**	26.1***
HS × S × C	8	0.01	0.02	0.005	12.4	28.4**	3241.8***	5.2	15,785.1	0.1	319.5*	0.1
Residual	54	0.08	0.06	0.003	8.5	7.7	90.8	82.2	15,466.5	44.0	324.0	0.3
Total	89	–	–	–	–	–	–	–	–	–	–	–

* Significant at 0.05 probability level; ** Significant at 0.01 probability level; *** Significant at 0.001 probability level

erties. Cv. 'Marcona' presented the highest values for in-hull weight and nut weight. In addition, cv. 'Fournat de Brézenaud' displayed the best scores for kernel weight, hull percentage, shelling percentage, kernel true density, and kernel and nut porosities. However, cv. 'Tuono' was characterized by the lowest values for in-hull weight, nut weight, kernel weight, kernel bulk density, and kernel and nut porosities. Cvs. 'Ferragnès' and 'Ferraduel' showed no significant differences between them in terms of in-hull weight, kernel weight, nut bulk density, and nut porosity. The same trend was observed between cvs. 'Marcona' and 'Tuono' concerning nut bulk density and kernel true density.

Mean Comparison Among Sites

Table 4 shows sites mean values of the studied gravimetrical properties. There were significant differences between the three sites for almost gravimetrical traits except for kernel bulk density. Bni Hadifa showed the best scores for in-hull weight, nut weight, kernel weight, nut true density, kernel true density, nut porosity, and kernel porosity. Nevertheless, this site presented the lowest values of hull percentage, shelling percentage, and nut bulk density. However, hull percentage and shelling percentage were better expressed in Tahar Souk. Furthermore, Tahar Souk and Aknoul showed no significant differences in terms of in-hull weight, kernel weight, kernel true density, nut bulk density, and nut porosities.

Mean Comparison Between Seasons

Table 5 summarizes harvest seasons mean values for the whole gravimetrical properties. There were significant differences between the two harvest seasons for gravimetrical properties except for kernel bulk density and nut porosity. The 2015 harvest season was found to have the greatest values for hull weight, nut weight, kernel weight, shelling percentage, and porosity. While, 2016 had higher scores for hull percentage, nut true density, kernel true density, nut bulk density, and kernel porosity.

Correlations Among Gravimetrical Properties

Table 6 summarizes the matrix correlations between the studied gravimetrical properties. Important associations were found between some characters. A strong positive correlation was recorded between in-hull weight and nut weight ($r = 0.902$***). Kernel weight showed a high positive correlation with in-hull weight ($r = 0.774$***) and nut weight ($r = 0.812$***). A highly significant association was found between nut porosity and kernel porosity ($r = 0.759$***). These stronger correlations were modeled

Table 3 Mean values of cultivars for in-hull weight (HW), nut weight (NW), kernel weight (KW), hull percentage (HP), shelling percentage (SP), nut true density ($N\rho_t$), nut bulk density ($N\rho_b$), kernel true density ($K\rho_t$), kernel bulk density ($K\rho_b$), nut porosity ($N\varepsilon$), and kernel porosity ($K\varepsilon$) of five almond cultivars grown in different environments of northern Morocco (Aknoul, Bni Hadifa, and Tahar Souk) during two harvest seasons (2015 and 2016). Means for each character followed by the same letter are not significantly different at $P<0.05$

Cultivar	HW (g)	NW (g)	KW (g)	HP (%)	SP (%)	$N\rho_t$ (Kg m^{-3})	$K\rho_t$ (Kg m^{-3})	$N\rho_b$ (Kg m^{-3})	$K\rho_b$ (Kg m^{-3})	$N\varepsilon$ (%)	$K\varepsilon$ (%)
Ferraduel	5.48 c	3.85 b	0.93 b	30.9 d	25.4 d	905.9 a	898.5 d	509.9 a	627.7 c	43.7 ab	30.1 d
Ferragnès	5.33 c	3.43 c	0.92 b	36.1 c	28.0 c	839.2 c	915.0 c	477.3 a	633.8 b	43.1 ab	30.7 c
Fournat de Brézenaud	5.96 b	3.00 d	1.12 a	49.8 a	38.6 a	660.0 e	953.7 a	338.8 b	600.2 d	48.9 a	37.0 a
Marcona	6.61 a	4.57 a	0.91 b	30.9 d	19.9 e	857.8 b	929.8 b	480.3 b	637.4 b	43.6 ab	31.2 b
Tuono	4.57 d	2.72 e	0.82 c	41.0 b	32.1 b	732.6 d	925.6 b	464.0 b	650.5 a	36.1 b	29.7 e

Table 4 Mean values of sites for in-hull weight (HW), nut weight (NW), kernel weight (KW), hull percentage (HP), shelling percentage (SP), nut true density ($N\rho_t$), nut bulk density ($N\rho_b$), kernel true density ($K\rho_t$), kernel bulk density ($K\rho_b$), nut porosity ($N\varepsilon$), and kernel porosity ($K\varepsilon$) of five almond cultivars grown in different environments of northern Morocco (Aknoul, Bni Hadifa, and Tahar Souk) during two harvest seasons (2015 and 2016). Means for each character followed by the same letter are not significantly different at $P<0.05$

Site	HW (g)	NW (g)	KW (g)	HP (%)	SP (%)	$N\rho_t$ (Kg m^{-3})	$K\rho_t$ (Kg m^{-3})	$N\rho_b$ (Kg m^{-3})	$K\rho_b$ (Kg m^{-3})	$N\varepsilon$ (%)	$K\varepsilon$ (%)
Aknoul	5.17 b	3.23 b	0.87 b	37.6 b	27.5 b	797.7 b	903.1 b	455.6 a	636.2 a	43.0 b	29.5 c
Bni Hadifa	6.55 a	4.38 a	1.03 a	33.8 c	24.6 c	839.9 a	948.7 a	449.7 b	633.3 a	46.4 a	33.2 a
Tahar Souk	5.06 b	2.93 c	0.91 ab	41.9 a	34.3 a	759.8 c	921.7 b	457.0 a	620.3 b	39.7 ab	32.6 b

Table 5 Mean values of years for in-hull weight (HW), nut weight (NW), kernel weight (KW), hull percentage (HP), shelling percentage (SP), nut true density ($N\rho_t$), nut bulk density ($N\rho_b$), kernel true density ($K\rho_t$), kernel bulk density ($K\rho_b$), nut porosity ($N\varepsilon$), and kernel porosity ($K\varepsilon$) of five almond cultivars grown in different environments of northern Morocco (Aknoul, Bni Hadifa, and Tahar Souk) during two harvest seasons (2015 and 2016). Means for each character followed by the same letter are not significantly different at $P<0.05$

Harvest season	HW (g)	NW (g)	KW (g)	HP (%)	SP (%)	$N\rho_t$ (Kg m^{-3})	$K\rho_t$ (Kg m^{-3})	$N\rho_b$ (Kg m^{-3})	$K\rho_b$ (Kg m^{-3})	$N\varepsilon$ (%)	$K\varepsilon$ (%)
2016	5.35 b	3.29 b	0.82 b	39.3 a	27.9 b	809.3 a	927.8 a	467.4 a	630.1 a	41.8 a	32.0 a
2015	5.83 a	3.74 a	1.05 a	36.2 b	29.7 a	789.0 b	921.2 b	440.7 a	629.6 a	44.4 a	31.5 b

through simple regressions, which were performed on mean values over cultivars, sites and harvest seasons (Fig. 1). Nut weight and kernel weight as dependent variables were regressed on in-hull weight as independent variable. In this regard, a high in-hull weight was related to both higher nut weight and kernel weight. In-hull weight could be a good predictor for nut weight and kernel weight since it explained more than 90 and 77% of their variance, respectively. In the same way, kernel weight and kernel porosity (dependent variables) were regressed on nut weight and nut porosity respectively. Kernel weight could be predicted from nut weight with an accuracy of more than 81%. The same trend was demonstrated for kernel porosity for which higher nut porosity was associated with great values of kernel porosity indicating that this latest could be estimated from nut porosity with an accuracy superior to 75%.

Cultivar, Site, and Harvest Season Discrimination by PCA

PCA was used as a multivariate method to better discriminate between cultivars, sites, and harvest seasons. The three first PCs were retained because they allowed explaining 86% of the total variability in our results. PC1, PC2, and PC3 accounted for 45%, 30%, and 11%, respectively. Points plotted on the surface delimited by axis 1 and 2 (Fig. 2) are related to cultivars, which seem to be distributed along PC1. Towards its positive direction, cvs. 'Ferraduel', 'Ferragnès', and 'Marcona' interacted with higher values of in-hull weight, nut weight, kernel weight, nut true density, nut bulk density, and kernel bulk density. Cv. 'Fournat de Brézenaud' interacted, on the negative side of PC1, with higher scores of hull percentage, shelling percentage, nut porosity, kernel porosity, and kernel true density. Cv. 'Tuono', plotted on negative direction of PC1 was associated with higher values of hull percentage and shelling percentage.

Table 6 Coefficients of Correlation among the studied traits: in-hull weight (HW), nut weight (NW), kernel weight (KW), hull percentage (HP), shelling percentage (SP), nut true density ($N\rho_t$), nut bulk density ($N\rho_b$), kernel true density ($K\rho_t$), kernel bulk density ($K\rho_b$), nut porosity ($N\varepsilon$), and kernel porosity ($K\varepsilon$) of five almond cultivars grown in different environments of northern Morocco (Aknoul, Bni Hadifa, and Tahar Souk) during two harvest seasons (2015 and 2016)

	NW	KW	HP	SP	$N\rho_t$	$K\rho_t$	$N\rho_b$	$K\rho_b$	$N\varepsilon$	$K\varepsilon$
HW	0.902***	0.774***	–0.342	–0.389	0.339	0.409 *	0.209	–0.092	0.165	0.456 *
NW	–	0.812***	–0.693**	–0.628**	0.552**	0.257	0.469**	0.122	–0.030	0.207
KW	–	–	0.026	0.334	–0.143	0.274	–0.153	–0.461*	0.148	0.489*
HP	–	–	–	0.648**	–0.643**	0.127	–0.662**	–0.395*	0.321	0.297
SP	–	–	–	–	–0.646**	–0.046	–0.572**	–0.571**	0.139	0.226
$N\rho_t$	–	–	–	–	–	–0.113	0.673**	0.341	–0.121	–0.184
$K\rho_t$	–	–	–	–	–	–	–0.435*	–0.032	0.620**	0.641**
$N\rho_b$	–	–	–	–	–	–	–	0.386*	–0.575**	–0.492*
$K\rho_b$	–	–	–	–	–	–	–	–	–0.338	–0.524**
$N\varepsilon$	–	–	–	–	–	–	–	–	–	0.759***
$K\varepsilon$	–	–	–	–	–	–	–	–	–	–

* Significant at 0.05 probability level; ** Significant at 0.01 probability level; *** Significant at 0.001 probability level

Similarly, points plotted on the plan determined by axis 1 and 2 were related to sites (Fig. 3). PC2 appears to discriminate between Bni Hadifa towards the positive direction of this component with higher scores of in-hull weight, nut weight, kernel weight, kernel true density, nut porosity, and kernel porosity. However, Aknoul and Tahar Souk were distributed on the negative side of PC2. Additionally, Tahar Souk interacted with the best scores of hull percentage and shelling percentage on one hand and Aknoul was associated with the greatest values of kernel bulk density and nut bulk density on the other hand.

Fig. 4 presents the distribution of harvest seasons on the surface determined by PC1 and PC3. The third component, which accounted for about 11% of total variability separated clearly between the two harvest seasons. 2015 harvest season interacted, on the negative values of PC3,

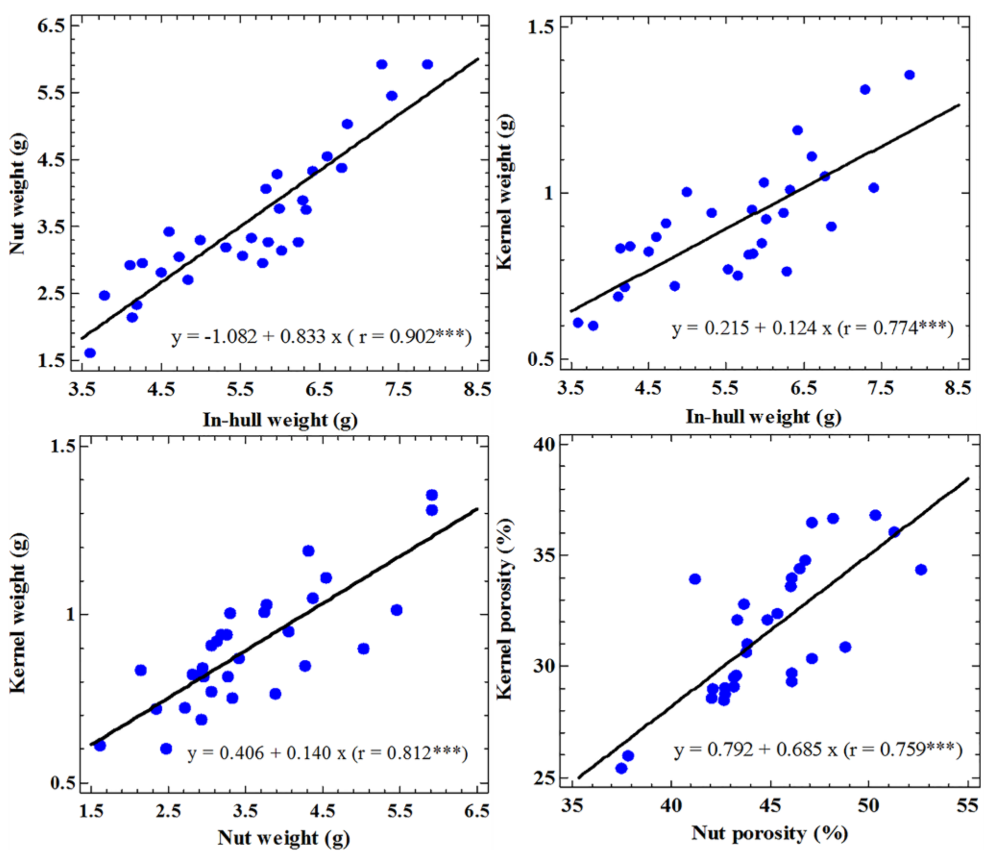

Fig. 1 Linear relationships between some gravimetrical traits of five almond cultivars grown in different environments in northern Morocco (Aknoul, Bni Hadifa, and Tahar Souk) during two harvest seasons (2015 and 2016). *r* correlation coefficient. *** indicate significance at 0.001 levels of probability. The 30 points plotted are mean values averaged over cultivars, sites and harvest seasons

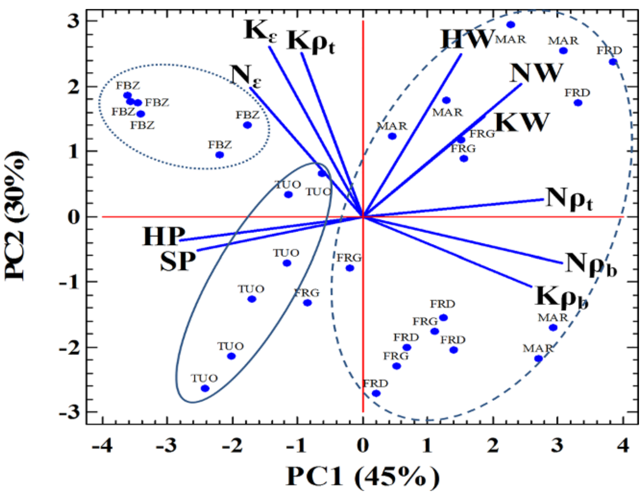

Fig. 2 Principal component analysis (PCA) projections on PC1 and PC2. The eigenvalues are symbolized as blue segments representing traits that most affect each principal component. The 30 points are cultivar mean values of each studied trait of five almond cultivars grown in different environments of northern Morocco (Aknoul, Bni Hadifa, and Tahar Souk) during two harvest seasons (2015 and 2016). *HW* in-hull weight, *NW* nut weight, *KW* kernel weight, *HP* hull percentage, *SP* shelling percentage, $N\varrho_t$ nut true density, $N\varrho_b$ nut bulk density, $K\varrho_t$ kernel true density, $K\varrho_b$ kernel bulk density, N_ε nut porosity, K_ε kernel porosity. *FRD* cv. 'Ferraduel', *FRG* cv. 'Ferragnès', *FBZ* cv. 'Fournat de Brézenaud', *MAR* cv. 'Marcona', and *TUO* cv. 'Tuono'

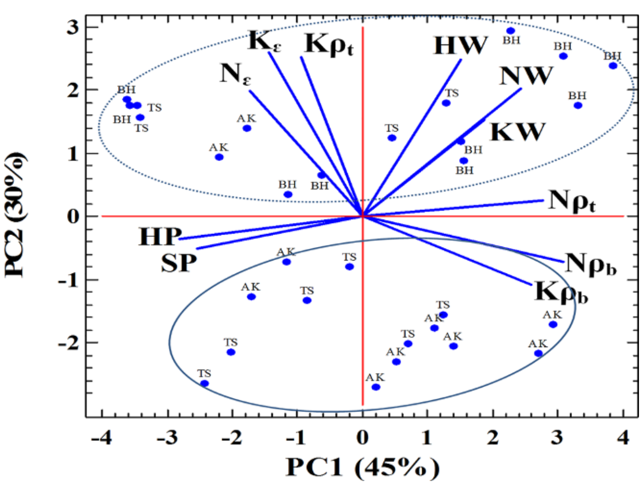

Fig. 3 Principal component analysis (PCA) projections on PC1 and PC2. The eigenvalues are symbolized as blue segments representing traits that most affect each principal component. The 30 points are site mean values of each studied trait of five almond cultivars grown in different environments of northern Morocco (Aknoul, Bni Hadifa, and Tahar Souk) during two harvest seasons (2015 and 2016). *HW* in-hull weight, *NW* nut weight, *KW* kernel weight, *HP* hull percentage, *SP* shelling percentage, $N\varrho_t$ nut true density, $N\varrho_b$ nut bulk density, $K\varrho_t$ kernel true density, $K\varrho_b$ kernel bulk density, N_ε nut porosity, K_ε kernel porosity. *AK* Aknoul, *BH* Bni Hadifa, and *TS* Tahar Souk

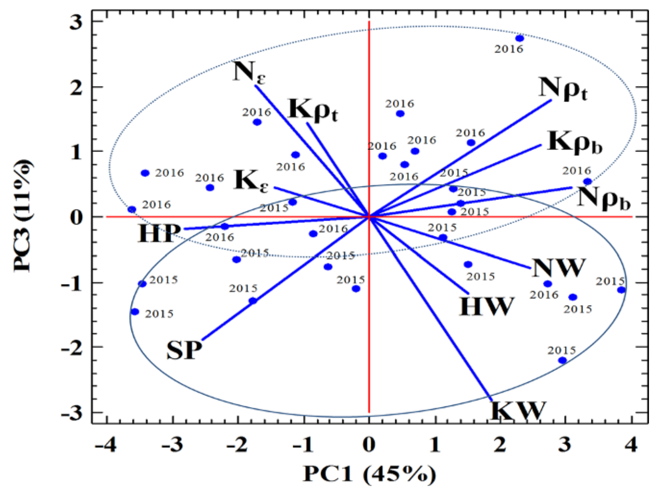

Fig. 4 Principal component analysis (PCA) projections on PC1 and PC3. The eigenvalues are symbolized as blue segments representing traits that most affect each principal component. The 30 points are year mean values of each studied trait of five almond cultivars grown in different environments of northern Morocco (Aknoul, Bni Hadifa, and Tahar Souk) during two harvest seasons (2015 and 2016). *HW* in-hull weight, *NW* nut weight, *KW* kernel weight, *HP* hull percentage, *SP* shelling percentage, $N\varrho_t$ nut true density, $N\varrho_b$ nut bulk density, $K\varrho_t$ kernel true density, $K\varrho_b$ kernel bulk density, N_ε nut porosity, K_ε kernel porosity. 2015 = harvest season of 2015 and 2016 = harvest season of 2016

with in-hull weight, nut weight, kernel weight, and shelling percentage. In contrast, 2016 harvest season plotted on the positive values of PC3, was associated with higher scores for the rest of gravimetrical traits. All these findings presented in Figs. 2, 3 and 4 confirmed the results of mean comparisons already reported in Table 3, 4 and 5.

Discussion

Fruit gravimetrical properties of major almond commercial cultivars in northern Morocco were reported in this work. Effects of growing area (three different sites) and harvest season (2015 and 2016) were also highlighted. It has been demonstrated that, all factors (genotypic, environmental, and climatic) impacted fruit gravimetrical traits in agreement with other similar studies (Kodad et al. 2011; Hussain et al. 2017; Eroğul and Oğuz 2018). In fact, hull percentage, nut true density, nut bulk density and kernel bulk density were mainly under genetic dependency, while shelling percentage, and nut and kernel porosities were equally determined by additive genotypic and edaphic factors. However, for the remaining traits environmental effects were more pronounced. As previously reported, environmental factors along with genetic control are known to impact both geometrical and gravimetrical fruit traits (Kodad et al. 2015; Rharrabti and Sakar 2016; Cosmulescu et al. 2017). In a seven years study, Ledbetter and Sisterson (2010) observed highly significant variabilities between harvest seasons with respect to in-hull weight, nut weight, and kernel weight. Moreover, the genetic control of these traits was highlighted by several works (Kester et al. 1977; Spiegel-Roy and Kochba 1981). It is worthy to underline the fact that physical characteristics of fruits (including gravimetrical ones) represent a quality feature of nuts (Cosmulescu et al. 2017). Almond hulls, which become dry at maturity, represent a potential source of useful foods, food additives, pharmaceuticals, and as supplemental livestock feed (Esfahlan et al. 2010), but also a natural source for dietary fibers and sweetener concentrate as pointed out by Takeoka and Dao (2003). In our results, the greatest values of hull percentage were recorded in cvs. 'Fournat de Brézenaud' (49.8%) and 'Tuono' (41.0%). Hence, these two cultivars may be considered as promising candidate for almond hulls source. In a similar study, Ledbetter and Sisterson (2010) found, for cv. 'Nonpareil', a hull percentage of 56.5% with large year-to-year fluctuations.

Besides, shelling percentage and shell hardness are the most important shell traits. These shell traits are inversely related to each other. They are very important for kernel protection during postharvest handlings and processing as reported by Socias i Company et al. (2008), who established a shell hardness classification as a function of shelling percentage as follows: 10–30% of shelling percentage for very hard shells and 30–50% for hard shells however a shelling percentage 50–70% fits soft shells. Commercial cultivars investigated here were of very hard shell (cvs. 'Marcona', 'Ferraduel', and 'Ferragnès') and hard shell (cvs. 'Fournat de Brézenaud' and 'Tuono') resulting in good kernel protection. Hence, these almond nuts could be stored for a long time if they are kept away from sunlight since intact hard shells protect kernels from both deterioration caused by molds and insect damage (Schirra 1997; Thompson et al. 1996). However, separating shell fragments from shelled nuts can be more difficult for hard-shelled cultivars, because of the similarities in density between the kernel and shell fragments (Schirra 1997). Kernel, the edible part of almond fruit, has great commercial and nutritive values. Almond kernels are divided into four groups according to Gülcan (1985): Very small (less than 0.9 g), small (0.9 to 1.1 g), medium (1.1 to 1.4 g), and large (1.4 to 1.8 g). Upon this classification, our cultivars were very small (cv. 'Tuono'), small (cvs. 'Marcona', 'Ferragnès', and 'Feraduel'), and medium (cv. 'Fournat de Brézenaud').

Other gravimetrical properties of great importance during postharvest handling include fruits density and porosity. In this regard, it has been demonstrated that bulk density and porosity are major considerations in designing near-ambient drying and aeration systems, as these properties impact on the airflow's resistance of the stored mass (Madamba et al. 1993; Agullo and Marenya 2005; Kashaninejad and Tabil 2009). In addition, these properties may be useful in the separation and transportation of the fruit by hydrodynamic means (Owolarafe et al. 2007). True density values found in our study were higher in almond kernel as compared to almond nut, but in all did not reach 1000 Kg m^{-3}, which represent the water density. This means that nut and kernel investigated here may be partially submerged in water when it is used as an aerodynamic carrier. Similarly to true density, bulk density of almond kernel in all cultivars was found to have great values as compared to almond nut. Moreover, values of bulk density were smaller than those of true density. This could be explained by voids that exist between fruits resulting in small values of bulk density (Owolarafe et al. 2007). Porosity, which is a key parameter in airflow circulation, was found to be significantly different among cultivars. The best scores of this gravimetrical trait of both almond nut and kernel were recorded in cv. 'Fournat de Brézenaud' because of its lower sphericity (data not published). However, lower values of porosity in nuts and kernels were recorded in the remaining cultivars which were marked by higher values of sphericity that ensures a more compact arrangement of the fruits. Density and porosity values reported in our work were in accordance with those reported in Aydin (2003). However, Ledbetter and Sisterson (2010) found higher values of kernel true density in cv. 'Nonpareil' with significant variability between harvest seasons. Furthermore, correlations among gravimetrical traits highlighted in the present work were supported by findings reported by other works (Sorkheh et al. 2010; Khadivi-Khub et al. 2016; Imani and Shamili 2018). Such associations among the traits could be attributed, in part, to the linkages or pleiotropic effects existing among the genes that encode for these traits (Hansche et al. 1972).

Discrimination between cultivars, sites, and harvest seasons was undertaken through PCA. This multivariate tool is widely used as a discriminative method among pomological traits (Sakar et al. 2017b; Milošević and Milošević 2017). In our data, the first component was genetic and accounted for about 45% of variability, along this component were distributed the studied cultivars, this could be explained by a differential genotypic expression. The second and the third component were of environmental extent and explained together around 41% of data variability. In addition, the second component separated between sites because of the pedological differences among the three localities. The third component was climate dependent because 2016 harvest season was marked by severe drought resulting in small fruit (in-hull weight, nut weight, and kernel weight) as compared to the 2015, which was a rainy season.

Conclusions

In this paper, gravimetrical properties of almond fruit in the most important cultivars grown in northern Morocco were reported. Significant differences were found between cultivars for almost investigated traits. Environmental (pedoclimatic) factors impacted to a large extent our data variability. Cv. 'Fournat de Brézenaud' performed better in terms of kernel weight, hull percentage, and shelling percentage as compared to the other cultivars. According to our results, cvs. 'Ferraduel', 'Ferragnès', and 'Marcona' produced fruits of very hard shell ensuring, thus, a good kernel protection suggesting its suitability for long-time nut storage if they are sheltered from sunlight. Results found as regards to bulk density, true density, and porosity should be taken into account for optimizing postharvest handlings such as aeration, drying, packing, and transportation.

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Conflict of interest E.H. Sakar, M.E. Yamani and Y. Rharrabti declare that they have no competing interests.

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