Summary

Owing to their high nutritional and economical values, cultivated almond (*Prunus dulcis* [Mill.] D.A. Webb) is one of the most important nut trees grown worldwide. In Morocco, this species is the main important among the rosaceous family. Despite its rank as the fourth global producer, Moroccan production (about 102085 tonnes of unshelled almonds) fluctuates considerably from year-to-year and remains relatively low as compared to USA and Spain. Moroccan orchards are mainly based on some commercial cultivars originated from France, Spain, and Italy. Occurrence of frost causes serious damages to almond flowers and fruitlets which threatens the production. The research works falling within the framework of this thesis were focused on three main axes: (i) Phenological characterization, (ii) assessment of fruit physical traits, and (iii) evaluation of kernel oil quality and almond cake as a by-product obtained after oil extraction. Our study concerned the main cultivars grown in Morocco 'Marcona', 'Fournat de Brézenaud', 'Ferragnès', 'Ferraduel', and 'Tuono'. To evaluate the effects of environmental conditions on phenology and fruit quality, our study was carried out across five different sites in northern (Aknoul, Bni Hadifa, and Tahar Souk) and eastern Morocco (Rislane and Sidi Bouhria) during three consecutive growing seasons.

In the first chapter, which was devoted to phenological characterization, we developed a phenological scale according to the code BBCH in which different growth stages were identified, codified, and described. Eight of the ten principal stages (0 − 9) from BBCH scale were divided into vegetative and reproductive phenologies. Vegetative phenology includes bud development (stage 0), leaf development (stage 1), shoot development (stage 3), and senescence and beginning of the rest period (stage 9). Reproductive phenology encompasses the four following stages: inflorescence emergence (stage 5), flowering (stage 6), fruit development (stage 7), and fruit maturity (stage 8). Phenological calendar of the five cultivars was established under the conditions of northern Morocco. In the second part of this chapter, and based on periodical visits and meteorological records in the five study sites, we determined the chilling requirements (chilling units, CU) and heat requirements using GDD and GDH models for flowering and ripening. CU ranged from low for the early and intermediate flowering cultivars ('Marcona' and 'Fournat de Brézenaud') to high for late flowering cultivars ('Ferragnès', 'Ferraduel', and 'Tuono'). GDD and GDH also differed significantly among cultivars, sites, and growing seasons. The third part of this chapter was devoted to the evaluation of frost susceptibility of flower buds using chlorophyll fluorescence (Fv/Fm). The outcomes of this part indicate a linear decrease of Fv/Fm, when regressed on incubation temperature, which translated by frost susceptibility for late-flowering cultivars 'Ferragnés' and 'Ferraduel', and a quadratic curve with an inflection point at -1°C indicating a frost tolerance for 'Tuono' and the early ('Marcona') and intermediate-flowering ('Fournat de Brézenaud'). However, 'Ferragnés' and 'Ferraduel' (with later flowering date) are not likely to be affected by low temperatures at the end of spring when there is no risk of frost.

In the second chapter of this thesis, we evaluated some physical properties of almond nuts and kernels. Geometrical determinations were performed both in nuts and kernels, and consisted of the nine following parameters: length (L), width (W), thickness (T), arithmetic mean diameter (D_a), geometric mean diameter (D_g), sphericity (Φ), volume (V), surface area (S_a) and projected area (P_a). ANOVA analyses showed that site, growing season, cultivar, and most of their interactions affected significantly all the parameters studied. L and Φ were genetically controlled, while T was environment-dependent for both nuts and kernels as well as D_g, V, S_a, Pa only for nuts. The rest of traits were equally determined by genotypic and environmental effects. Mean comparisons between cultivars showed that 'Marcona' and 'Fournat de Brézenaud' displayed the highest values of all geometrical properties. Gravimetrical measurements consisted in: In-hull weight (HW), nut weight (NW), kernel weight (KW), hull percentage (HP), shelling percentage (SP), true density (ρ_t), bulk density (ρ_b), and porosity (ε). The outcomes of ANOVA demonstrated that cultivar, site, growing season, and their interactions affected significantly most gravimetrical traits. In fact, HP, ρ_b in kernels, and both ρ_t and ρ_b in nuts were mainly under genotypic dependency, while growing season (climatic factor) was the main variability source in KW. Furthermore, site (edaphic factor) was the most important in determining HW, NW, and ρ_t in kernels, while SP, and ε in kernels and nuts were controlled jointly by genetic and edaphic factors. Almond kernels from our cultivars were medium ('Tuono', 'Ferraduel', 'Ferragnès', and 'Marcona'), and large ('Fournat de Brézenaud'). Furthermore, corresponding nuts were hard ('Fournat de Brézenaud', 'Tuono', and 'Ferragnès') to very hard shelled ('Ferraduel' and 'Marcona'). Among sites, fruits harvested from sites of eastern Morocco performed better in terms of HW, NW, KW, ρ_b, and ρ_t. Whereas, Aknoul and Tahar Souk (northern Morocco) had the greatest values of HP and ε in both nuts and kernels. Kernel color indices were also evaluated: Brightness index (L*), redness index (a*), yellowness index (b*), chroma (C*), hue angle (H*), and metric saturation (S*). The outcomes of ANOVA demonstrated significant effects of all factor (cultivar, growing season, and site) and site by cultivar interaction on almost studied kernel color properties. However, the majority of these properties was genotypic dependent. 'Marcona' showed the highest L*, while 'Ferragnès' and its pollinator 'Ferraduel' displayed greater scores of a*, b*, C*, and S*. Among sites, Sidi Bouhria was found to have the lowest L* but higher values of a*,

H*, and S*. Moreover, Bni Hadifa displayed higher L*, b*, and C*. For growing seasons, 2016 had the highest values of most color indices.

The third chapter was devoted to the assessment of some almond oil quality traits and determination of the nutritional quality of almond cake. After press extraction, oil content (OC) was calculated. Oil quality determinations consisted of acid value (AV), peroxide value (PV), UV absorption coefficients (K_{232} and K_{270}), and polyphenols content (PP), fatty acids composition was determined using CG on samples collected in 2017 growing season at Aknoul and Sidi Bouhria. Total saturated fatty acids (SFA), monounsaturated fatty acids (MUFA), polyunsaturated (PUFA), and Oleic acid/ Linoleic acid ratio (O/L) were computed. The outcomes of ANOVA showed that all factor (cultivar, site, growing season) and most of their interactions affected significantly the studied physico-chemical traits, being cultivar the main source of variability. 'Marcona' showed its superiority for OC (57.70 % DM), while 'Fournat de Brézenaud' presented the highest values of PP (0.84 mg GA/g oil), AV (0.90 % Oleic acid), and PV (0.42 meqO_2/kg of oil). The highest values of K_{232} (1.99) and K_{270} (0.20) were recorded in 'Ferragnès' and 'Ferraduel', respectively. Among sites, Sidi Bouhria showed the greatest OC (54.57), PP (0.81), K_{232} (1.71), and K_{270} (0.17). Concerning growing season, 2016 was characterized by its higher scores for all studied traits. Our results for fatty acids revealed the presence of 11 fatty acids with wide variabilities between cultivars and sites. However, major fatty acids were: Oleic (C18:1), linoleic (C18:2), palmitic (C16:0), stearic (C18:0), and palmitoleic (C16:1). MUFA (mainly C18:1) were most important among fatty acids followed by PUFA (mostly C18:2) and SFA (C16:0). O/L is a good kernel quality criterion because higher values of this ratio indicate higher oil stability and kernel quality. In our results, O/L varied significantly among cultivars with the highest value found in 'Ferraduel' (4.55) and the lowest one in 'Fournat de Brézenaud' (3.20). Our results demonstrated that oil samples obtained were generally of excellent quality with low values of AV, PV, K_{232}, and K_{270} on one hand and higher values of PP and O/L on the other hand. In order to characterize almond cake as a by-product of almond, we evaluate proteins, moisture, ash, residual oil, carbohydrates, energy value and pH in the press cake. ANOVA analyses showed significant effects of cultivar, growing season, and site. Among cultivars, 'Marcona' showed the highest value of residual oil and energy value, 'Fournat de Brézenaud' presented the best score of proteins, and 'Ferragnès' displayed the greatest value of ashes and carbohydrates. With respect to sites, the eastern sites exhibited the greatest values of proteins, residual oil, ashes, energy value but lower moisture content and carbohydrates. Concerning growing seasons, 2018 was a rainy year resulting in almond cake of higher moisture, but lower proteins, ashes, residual oil, and a lower energy value.

Keywords: Phenology, BBCH scale, chilling and heat requirements, fruit quality, pomological traits, kernel oil, almond cake, genotypic and environmental effects, multivariate statistical analyses.