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in

Zakynthinos G. (ed.).
XIV GREMPA Meeting on Pistachios and Almonds

Zaragoza : CIHEAM / FAO / AUA / TEI Kalamatas / NAGREF
Options Méditerranéennes : Série A. Séminaires Méditerranéens; n. 94

2010
pages 255-260

Almond breeding and evaluation activities in Central California: Past and future

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Abstract. Almond breeding and evaluation efforts at the Agricultural Research Service resumed during the late 1980s after a lapse of nearly 20 years. Breeding efforts from the 1950s through the early 1970s led to a diverse collection of advanced selections, some being suitable as pollenizers for the important 'Nonpareil' cultivar. Current evaluation efforts are now further characterizing the collection, and some selections are being used in a new breeding effort to develop self-compatible almonds. Through K-means analyses, we have identified those advanced selections from the former breeding effort that were most similar to 'Nonpareil' in bloom phenology and nut/kernel characteristics. In long term storage trials, we have identified several advanced selections with reduced pellicle luminosity degradation rates as compared with 'Nonpareil'. The 'Tuono' cultivar has been our exclusive source of self-compatibility in the new breeding effort, with planned hybridizations emphasizing those advanced selections that are homozygous for sweet kernel. New self-compatible accessions are being identified in segregating seedling populations, and we currently evaluate 50–70 self-compatible accessions annually for nut/kernel quality. Recent evaluation efforts have demonstrated significant differences in shell cracking strength among almond varieties that are independent of an accession's kernel percentage, suggesting shell compositional or morphological differences. These differences may have implications in the use of specific shell types for granular activated carbons, or other value-added product applications.

Keywords. Color – Kernel quality – *P. dulcis* – Pellicle – Self-compatibility – 'Tuono'.

Activités d'amélioration et d'évaluation d'amandiers dans le centre de la Californie : passé et futur

Résumé. *Les efforts pour l'amélioration génétique et l'évaluation de l'amandier ont repris à l'Agricultural Research Service à la fin des années 1980 après une interruption de près de 20 ans. Les efforts de sélection à partir des années 1950 jusqu'au début des années 1970 ont conduit à une vaste collection de sélections avancées, certaines étant aptes comme pollinisateurs pour l'important cultivar 'Nonpareil'. Les efforts actuels d'évaluation visent maintenant à caractériser davantage la collection, et certaines sélections sont utilisées dans un nouvel effort pour développer des amandiers auto-compatibles. Grâce à des analyses de moyennes K, nous avons identifié les sélections avancées de l'ancienne étape d'amélioration qui ont été le plus semblables à 'Nonpareil' dans la phénologie de la floraison et les caractéristiques de l'amandon. Lors d'essais de stockage à long terme, nous avons identifié plusieurs sélections avancées à taux réduits de dégradation de la pellicule à la luminosité par rapport à 'Nonpareil'. Le cultivar 'Tuono' a été notre seule source d'auto-compatibilité dans les nouveaux efforts de sélection, avec des hybridations prévues en mettant l'accent sur les sélections qui sont homozygotes pour l'amande douce. De nouvelles accessions auto-compatibles sont en cours d'identification dans les plants de populations ségrégantes, et nous évaluons actuellement 50-70 accessions compatibles par an pour la qualité de l'amande. Les récents efforts d'évaluation ont montré des différences significatives dans la résistance à la fissuration de la coque entre variétés d'amandes, qui sont indépendantes du pourcentage d'amande des accessions, suggérant des différences morphologiques ou de composition de la coque. Ces différences ont des implications quant à l'utilisation de certains types de coque pour faire du charbon actif granulaire, ou autres types de produits à valeur ajoutée.*

Mots-clés. *Couleur – Qualité de l'amande –* P. dulcis *– Pellicule – Auto-compatibilité – 'Tuono'.*

I – Introduction

Prior to 1948, a combined almond breeding effort existed between the Agricultural Research Service and the University of California at Davis. ARS later moved its breeding efforts to the Fresno, CA under the direction of Dr. Bob Jones. A major objective of the program at the time was to develop pollination partners for the important 'Nonpareil' cultivar that could both pollenize and be harvested at the same time. Pollination partners would need to be pollen intercompatible with 'Nonpareil' and have kernels with dimensional similarities as compared to 'Nonpareil's such that the crops could be harvested and processed simultaneously without a penalty for having a mixed lot. The cultivar 'Vesta' was introduced for just that purpose in 1968 (Jones, 1968). Late bloom period and a smooth, light colored pellicle were two other objectives initiated by Dr. Jones during his tenure at the Fresno location. Resultant from his hybridization efforts, numerous advanced almond selections were being trialed at various San Joaquin Valley locations throughout the 1960s and 1970s. 'Titan' (Weinberger, 1971) was the only other almond cultivar introduced by ARS prior to Dr. Jones retirement in 1973. 'Titan' was not developed to be a new edible almond, but its late bloom interval that matched with the peach rootstock 'Nemaguard' made it an attractive source for peach-almond hybrid seed desired by nurseries as vigorous rootstocks for almonds (Jones, 1972). The introduction of 'Titan' and the retirement of the principal investigator responsible for almond research at the Fresno location marked an end of the initial ARS almond breeding effort in Central California. Further breeding and almond evaluation research would not resume for nearly 20 years.

II – Materials and methods

Advanced almond selections from the former ARS almond breeding program were identified and collected from grower orchards in the central San Joaquin Valley where they had been established in commercial trials. The selections were propagated onto 'Nemaguard' rootstock and planted in the San Joaquin Valley Agricultural Sciences Center (SJVASC) research orchard in Parlier, CA. Commercial almond cultivars were similarly planted at the SJVASC as bare root nursery stock. The cultivar 'Tuono' was established at the SJVASC under post-entry quarantine in 1993 for use in developing new seedling populations segregating for self-compatibility.

Floral self-compatibility of seedlings was determined using large nylon mesh bags affixed to flowering branches pre-anthesis (Burgos *et al.*, 1997), and evaluated for fruit set approximately six weeks after full bloom. Bloom and hull split phenology were scored subjectively every two to three days through visual observations. Trees were harvested at 100% hull split or later, and nuts were allowed to air dry on the orchard floor prior to collection. For nut and kernel laboratory evaluations, nut samples were further dried at 50℃ for approximatel y 24 h. Standard quality evaluations included nut and kernel mass, kernel percentage, pellicle color analysis (luminosity, chroma and hue), kernel flavor (subjective) and kernel dimensional analysis. To evaluate cracking behavior, field collected samples were processed in a research-sized commercial almond cracking unit (Ledbetter and Palmquist, 2006a). Evaluations of either advanced almond selections or newly fruiting seedlings were typically compared with evaluations of 'Nonpareil' and 'Padre' cultivars for the same characteristics.

III – Results and discussion

With the collection of advanced selections and industry standard cultivars in place at the research location, preliminary evaluations were conducted to identify those selections that were most similar to commercial cultivars in bloom, vegetative and carpological characteristics. Eight of the 24 evaluated ARS almond accessions clustered with 'Nonpareil' in K-means analyses

(Ledbetter and Palmquist, 2002b), including 'Vesta', corroborating its dimensional similarity to 'Nonpareil' as originally expressed (Jones, 1968). However, in bloom evaluations from 1996 through 1999, 'Vesta' effectively matched bloom interval with 'Nonpareil' in only one of the four years (Ledbetter and Palmquist, 2002a), suggesting a possible reason why the California almond industry never fully adopted this variety.

1. Continued evaluations of self-incompatible advanced selections

Several self-incompatible advanced selections from the earlier breeding effort are currently being trialed in commercial situations for their yield potential and use as pollination partners for 'Nonpareil'. Several advanced selections have kernel dimensions and pellicle color that are very comparable to 'Nonpareil', and similar harvest periods suggest that the crops could be combined. New developments in kernel separation technology have made it easier to remove double kernels from the shelling line, making several advanced selections more potentially worthy now as compared to when they were first under commercial trial in the 1970s. In a replicated field trial, selections 23.5-16 and 23-122 did not differ significantly ($p < 0.05$) from 'Nonpareil' in kernel mass, kernel length or width, nor in pellicle color coordinates luminosity and hue (Ledbetter and Palmquist, 2006a). Pellicle chroma values of 'Nonpareil' and 23.5-16 did not differ significantly ($p < 0.05$), nor did pre- or post-cracking levels of sticktights. Given the known pollen intercompatibility between 23.5-16 and 'Nonpareil', bloom synchronicity and the nearly identical fruit development periods, advanced selection 23.5-16 appears worthy of larger-scale commercial evaluations as a potential production partner for 'Nonpareil'.

Some of the advanced ARS almond selections have also been evaluated for their capacity to retain product quality during long term storage under various temperature regimes. The large volume of harvested California almonds requires year-round storage during marketing, with storage conditions varying widely. Kernels of 'Nonpareil', 'Padre' and three advanced almond selections were sampled periodically for pellicle color values during an 11-month storage period at three temperatures (2, 22 and 32°C). Rates of pellicle color degradation increased in all kernel samples with an increase in storage temperature. However, 'Nonpareil' had the greatest percentage decrease in pellicle luminosity (36.9%) when averaged across the storage temperatures (Ledbetter and Palmquist, 2006b). Advanced selections K3-90 and 82-73, both with pre-storage pellicle luminosity values not differing from 'Nonpareil', demonstrated reduced percentage decreases in pellicle luminosity (27.2 and 29.1%, respectively) as compared with 'Nonpareil'. Future postharvest research with these accessions may examine changes in antioxidant profiles during a prolonged storage period.

The current worldwide interest in utilizing high-volume agricultural by-products in value-added applications has led to evaluations of specific almond shell types from the breeding program. Valuable by-products are being obtained from processed almond shells (Font *et al.*, 1988; Toles *et al.*, 2000; Ahmedna *et al.*, 2004), but to date, published studies have treated almond shells as only a homogeneous substrate. By defining the chemical and physical characteristics of almond shells more precisely, researchers will better understand which specific almond shell feedstocks are best suited for specific industrial applications. While evaluating almond shell characteristics of eight diverse almond accessions, shell bulk density and shell cracking strength were found to vary significantly ($p < 0.01$). As expected, there was a significant ($p < 0.01$) negative correlation between shell cracking strength and the accession's kernel percentage (Ledbetter, 2007). But in some specific cases, cracking strength was independent of kernel percentage, suggesting either varietal compositional differences, or altered shell morphology affecting shell strength.

2. Resumption of breeding activities for self-compatibility

In 1991, an early-ripening accession of *Prunus webbii* was obtained from the USDA Germplasm Repository for hybridizations with both commercial cultivars and advanced almond selections from the breeding program. The bitter-kerneled *P. webbii* was a useful parent in these testcrosses to identify homozygous sweet kernel accessions (Ledbetter and Pyntea, 2000). Homozygous sweet kernel parents were then used preferentially in crosses with 'Tuono', due to its heterozygous status at the kernel flavor locus (Dicenta and García, 1993). Breeding efficiency was thus increased as bitter-kerneled seedlings would not be present in such seedling populations. Hybridizations with 'Tuono' began in 1996 and continued through the 2000 bloom period.

Evaluation of the seedlings produced from hybridizations between 'Tuono' and California adapted self-incompatible accessions began in 2000. Bitter kernel seedlings are rouged from the progenies prior to any determination of self-compatibility. The self-compatibility status is typically examined through pre-anthesis bagging of branches in 4th leaf trees. After identifying self-compatible trees, hull split and bloom phenology data are collected during the appropriate timeframes. First year nut and kernel lab evaluations involve basic dimensional, gravimetric and color analyses. Blind subjective analyses for kernel attractiveness and degree of wrinkling are conducted after all objective lab evaluations are completed. These subjective analyses are used primarily to further rouge seedlings with low kernel quality from progenies. Self-compatible trees that survive their first round of evaluation are propagated to rootstocks during dormancy and established in a second test orchard. The seedling trees are further evaluated the subsequent year, along with newly identified self-compatible seedlings. Second year evaluations also include a larger field sample of nuts to examine cracking performance as compared with industry standards 'Nonpareil' (soft shell) and 'Padre' (hard shell). To date, the most unexpected result from these 'Tuono' hybridizations has been the high quantity of seedlings having a kernel percentage greater than 50%.

Important kernel characters (Table 1) and phenological data (Table 2) are provided for five valuable self-compatible accessions as compared with 'Nonpareil'. Arising from hybridizations with 'Tuono' in 1999, we are now able to evaluate carpological quality and important phenologies of these accessions when propagated on a standard rootstock. Further, these advanced self-compatible selections (and others) have now been used as parents in the next breeding generation. With regard to the self-compatible trait, we expect higher breeding efficiency in this next generation, as both parents used in most of these hybridizations carried the self-compatible allele.

Table 1. Kernel characteristics of five self-compatible almond selections as compared with 'Nonpareil'. Values represent 3-year averages (2005-2007) from kernels harvested at the SJVASC in Parlier, CA

	Kernel %	Kernel wt (g)	Kernel ratios		
			Len:Wid	Len:Thick	Wid:Thick
Y113-87	52.6	1.35	2.17	3.56	1.63
Y116-152	34.1	1.11	1.53	2.65	1.74
Y120-74	35.6	1.02	1.63	3.34	2.05
Y121-42	53.8	0.94	1.72	3.01	1.75
Y121-58	55.7	0.95	1.88	2.94	1.56
'Nonpareil'	64.1	1.17	1.88	3.02	1.61

Based on overall superior performance in repeated annual quality evaluations, four self-compatible accessions have been established in isolated commercial trials to determine their yield potential, both with and without bee visitation. Cumulative kernel yield over several production seasons will be a predominant factor in determining the fate of these selections. As elite seedlings are identified from the next generation of hybrids, future grower trials will evaluate their yield potentials in isolated commercial conditions.

Table 2. Bloom and hull splits phenologies (2005-2007) of five self-compatible almond selections as compared with 'Nonpareil'. Data were collected at the SJVASC in Parlier, CA

		Bloom dates		Hull split dates	
		First	Full	Begins	Finishes
2007	Y113-87	19 Feb	27 Feb	27 June	31 July
	Y116-152	23 Feb	5 Mar	31 July	21 Aug
	Y120-74	20 Feb	27 Feb	27 June	24 July
	Y121-42	20 Feb	5 Mar	3 July	14 Aug
	Y121-58	23 Feb	8 Mar	18 July	14 Aug
	'Nonpareil'	16 Feb	2 Mar	3 July	21 Aug
2006	Y113-87	13 Feb	24 Feb	17 July	21 Aug
	Y116-152	22 Feb	6 Mar	4 Aug	14 Aug
	Y120-74	14 Feb	25 Feb	3 July	27 July
	Y121-42	15 Feb	1 Mar	28 July	14 Aug
	Y121-58	16 Feb	25 Feb	17 July	21 Aug
	'Nonpareil'	10 Feb	23 Feb	17 July	14 Aug
2005	Y113-87	23 Feb	3 Mar	22 July	9 Aug
	Y116-152	25 Feb	5 Mar	23 Aug	20 Sept
	Y120-74	19 Feb	4 Mar	24 June	26 July
	Y121-42	26 Feb	6 Mar	21 July	9 Aug
	Y121-58	24 Feb	4 Mar	19 July	16 Aug
	'Nonpareil'	17 Feb	26 Feb	4 July	2 Aug

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