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Abstract. Due to the recent sharp increase in prices, the almond has become a very profitable culture. This has changed the landscape, not only for the productive sector, but also for breeders that have to satisfy the new demands of nurseries, growers, industry and consumers. The traditional goals of almond breeding in the Mediterranean basin, like late flowering and self-compatibility, currently allow the profitable almond cultivation in cold areas. The new extra-late flowering cultivars are allowing its cultivation in extremely cold areas, in which almonds had never been cultivated. In these areas, early maturation will be an essential trait of new cultivars. In this new environment, resistance to pests and diseases will be a new challenge for breeders, to reduce production costs, develop an agriculture friendly with the environment and produce healthier almonds. Due to the huge demand of almonds, the prices of different cultivars have approached and so, productivity will be the main trait over any other characteristic. However, almond quality will be a significant commitment in the future by designing cultivars for each industrial use. Although modern irrigated plantations, as Californian or Australian, are being imposed in many areas, in the Mediterranean basin there are thousands of rainfed hectares, for which we will have to bred suitable cultivars and rootstocks, and apply appropriate techniques of cultivation. Biotechnological advances will be very useful, facilitating breeders' efforts by means of Marker Assisted Selection (MAS) for the main characteristics (flowering time, self-compatibility, bitter taste) or molecular identification of cultivars. Breeders have the responsibility to obtain new good cultivars, which must be seriously evaluated in different growing areas and culture conditions before offering them to nurseries and growers.

Keywords. *Prunus dulcis* – Cultivars – Breeding – Flowering time – Self-compatibility.

Amélioration génétique de l'amandier: important enjeux et défis pour la recherche

Résumé. *En raison de la forte et récente augmentation des prix, l'amande est devenue une culture très rentable. Cela a changé le paysage, non seulement pour le secteur de la production, mais aussi pour les améliorateurs qui doivent satisfaire les nouvelles exigences des pépiniéristes, des producteurs, de l'industrie et des consommateurs. Les objectifs traditionnels de l'amélioration de l'amandier dans le bassin méditerranéen, comme la floraison tardive et l'auto-compatibilité, permettent actuellement la culture de l'amandier rentable dans des zones froides. Les nouveaux cultivars à floraison extra-tardive permettent sa culture dans des zones extrêmement froides, dans lesquelles cette espèce n'a été jamais cultivée. Dans ces zones, la maturation précoce sera une caractéristique essentielle pour les nouveaux cultivars. Dans ce nouvel environnement, la résistance aux ravageurs et aux maladies sera un nouveau défi pour les améliorateurs afin de réduire les coûts de production, de développer une agriculture respectueuse de l'environnement et de produire des amandes saines. En raison de l'énorme demande d'amandes, les prix des différents cultivars ont approché et ainsi, la productivité sera le trait principal sur toute autre caractéristique. Cependant, la qualité de l'amande sera un engagement important à l'avenir en concevant des cultivars pour chaque usage industriel. Bien que les plantations irriguées modernes, comme les californiennes ou australiennes, sont imposées dans de nombreux domaines, dans le bassin méditerranéen, il y a des milliers d'hectares non irriguées pour lesquelles nous aurons besoin des cultivars et des porte-greffes appropriés et d'appliquer des techniques appropriées de culture. Les progrès de la biotechnologie seront très utiles, ce qui facilite les efforts des améliorateurs au moyen de la sélection assistée par marqueurs (MAS) pour les principales caractéristiques (date de floraison, l'auto-compatibilité, le goût amer) ou identification moléculaire des cultivars. Les améliorateurs ont la responsabilité d'obtenir de nouveaux cultivars, qui doivent être sérieusement évalués dans des différentes zones de culture et des conditions de culture avant de les offrir aux pépinières et aux producteurs.*

Mots-clés. Prunus dulcis *– Cultivars – Amélioration génétique – Période de floraison – Auto-compatibilité.*

Not one man in a thousand has accuracy of eye and judgment sufficient to become an eminent breeder. If gifted with these qualities, and he studies his subject for years, and devotes his lifetime to it with indomitable perseverance, he will succeed, and may make great improvements; if he lacks any of these qualities, he will assuredly fail.

Charles Darwin 1859, The Origin of Species.

I – Almond breeding and new cultivars

The almond breeding is aimed at solving the problems of the culture by obtaining new cultivars. Looking at the high almond yields produced in the USA or Australia (more than 2000 kg of kernel per hectare), we might think that the growers in these countries have no problems, or at least not as important as in other countries, and therefore they do not need much to improve their varieties. In the other producing countries (such as the Mediterranean or the Middle East countries), although there are modern plantations with high yields (similar to American and Australian), the general situation is of low yields (about 100 kg of kernel per hectare), mainly due to a culture under dry conditions or with deficient irrigation, and with frequent problems of pollination and spring frosts.

As a result of the age of the crop and the heterogeneity in the producer regions, the varietal situation is different in both environments. In the USA and Australia, the predominant cultivar is 'Nonpareil', which represents 40% and 50% respectively. 'Nonpareil' cultivar is highly adapted to environmental, cultural and commercial conditions of these countries. Other important cultivars grown in these countries are 'Carmel', 'Butte', 'Prize' and 'Monterrey'. In Mediterranean and near Eastern countries many local cultivars adapted to each area, along with new cultivars recently obtained in breeding programs, mainly from French and Spanish, are nowadays cultivated.

These new cultivars are gradually displacing traditional cultivars for their self-compatibility and late flowering time, which is a great advantage in colder areas. The more important breeding programs have been the French of INRA (with cultivars like 'Ferragnès', 'Ferraduel', 'Lauranne' and 'Mandaline'), the Spanish of IRTA-Constantí ('Francolí', 'Masbovera', 'Glorieta', 'Vayro', 'Constantí', 'Marinada' and 'Tarraco'), CITA-Zaragoza ('Ayles', 'Guara', 'Moncayo', 'Blanquerna', 'Cambra', 'Felisia', 'Soleta', 'Belona', 'Mardía' and 'Vialfás') and CEBAS-CSIC ('Antoñeta', 'Marta', 'Penta' and 'Tardona'). We must emphasize the great diffusion of French cultivars 'Ferragnès' and 'Ferraduel' in several European countries, and of 'Guara' specifically in Spain. Despite the held predominance of 'Nonpareil' in the USA, there are important public and private breeding programs, and several new cultivars have been released ('Avalon', 'Carmel', 'Butte', 'Father', 'Price', 'Sonora', 'Sweetheart', 'Winter', 'Independence' and 'Folsom'). Independence cultivar is the first American cultivar fully self-compatible obtained to date. The Australian breeding program is more recent, but nevertheless, it has obtained very interesting advanced selections under evaluation.

II – Genetic control and inheritance of traits

But these new cultivars are not the only interesting results of the breeding programs. The study of the obtained progenies for their selection has allowed the researchers to advance in the knowledge of the genetic control of quantitative traits, such as flowering and ripening time, productivity and fruit characteristics (Dicenta *et al.,* 1993a and b; Sánchez-Pérez *et al*., 2007; 2012; Martínez-García *et al*., 2014) and qualitative, as seed bitterness and self-compatibility (Dicenta and García, 1993b; Dicenta *et al*., 2007). This information now allows, depending on the selected progenitors, to predict the value of the seedlings for each characteristic, since heritability of the main traits is usually high.

Furthermore, the knowledge of the *S*-genotype for floral incompatibility of the parents to be used in crosses allows the breeders to design different strategies for obtaining 100% of self-compatible seedlings in the new offspring (Ortega and Dicenta, 2003). Similarly, knowing the genotype of the parents for the seed bitterness, we can avoid the appearance of bitter descendants in the offspring (Dicenta and García 1993b; Dicenta *et al.*, 2007).

There have also been significant advances in the field of floral biology, which have established the factors that affect the flowering time (Egea *et al.*, 2003; Sánchez-Pérez *et al.*, 2012; 2014), pollination and fruit set (Dicenta *et al.*, 2002, Egea *et al.,* 2002; Ortega *et al.*, 2004) more favourable for abundant and stable yields. The analysis of the *S*-genotype currently allows the early selection of self-compatible seedlings after germination of obtained seeds, and the design of new plantations to ensure the cross-compatibility between cultivars (Ortega and Dicenta, 2003; 2004). The demonstration that self-fertilization is as efficient as the cross-fertilization regarding fruit set and fruit characteristics, today enables profitable solid plantations of self-compatible cultivars, as it occurs in other fruit species (Dicenta *et al.*, 2002; Ortega *et al.*, 2006; Martínez-García *et al.*, 2011).

Furthermore, the development of molecular markers type SSR is allowing the unequivocal molecular identification of cultivars (Sánchez-Pérez *et al.*, 2006), which is revealing cases in which a given cultivar was known by different names or, opposite, the use of the same name for different cultivars. Some examples include the existence of several 'Marcona' and 'Desmayo Largueta' types in Spain (Martínez-García *et al.*, 2011), the coincidence of the cultivar known in Spain as 'Felipa' with the traditional Italian 'Filippo Ceo' or that the released 'Supernova' was actually the ancient Italian 'Tuono' (Marchese *et al.*, 2008). More recently, analysing 35 SSRs in samples of 'Tuono' and 'Guara' cultivars from four research centres (IRTA-Constantí, INRA-Avignon, University of Bari and CEBAS-CSIC of Murcia) researchers have shown that 'Guara', the most cultivated cultivar in Spain in recent years, it is actually the Italian cultivar 'Tuono' (Dicenta *et al.*, 2015). For their high performance, SSRs are nowadays an indispensable tool in the fight against fraudulent multiplication of protected cultivars.

On the other hand, genetic mapping together with the study of the offspring has allowed the identification of different QTLs for flowering, ripening and fruit traits and it is facilitating the development of molecular markers for these characteristics, which could be used in the early selection medium term (Sánchez-Pérez *et al.*, 2007; 2010; 2012; 2014), together with other tools such as the correlation between traits (Dicenta *et al.*, 2005).

All these biotechnology tools are improving the efficiency of breeding programs, enabling a more efficient selection of the most interesting genotypes. In spite of this progress, the breeder always will have to continue the creation of new genotypes and their selection based on their agronomic behaviour in the field.

III – New goals for almond breeding

Until now, the breeding objectives, mainly in the Mediterranean basin, have aimed to obtain self-compatible and late-flowering cultivars to increase the fruit set and to avoid the spring frosts damages. Fruit quality and ease of management of the trees have also been important traits.

But what really matters for the growers, is the productivity of the plantation in terms of net income per hectare. This means incomes (kilograms of kernel multiplied by the prize of the kernel) minus expenses (including cultivation and all aspects related to the cultivar that affect to production costs). This obvious objective is especially important now, where the high demand for almonds in Russia, India, China and South Korea have pushed up prices, for example to triple in Spain. Result of this high demand, the important traditional difference of prices between different cultivars has approached, giving prominence to the quantity over quality, with some exceptions. Despite this fact, it is likely that in the medium-long term the market will demand breeders for almonds with different characteristics depending on their industrial use (different chemical composition, size or shape for the manufacture of nougat, marzipan, chocolates, snacks, etc.). But in short term, as we have indicated, the main objective will remain the high productivity.

Moreover, at present, new opportunities for almond breeding, which should play a meaningful role in the economic performance of plantations, are open. Early maturation has always been an interesting feature in almond but has not been paid sufficient attention. In warmer areas, it allows harvesting of the crop before the high summer temperatures, facilitating the preparation of the tree for the adequate development for the following year. In cold areas also prevents excessive delay in ripening. Some late ripening cultivars, in cold areas, can be harvested in October or November, when low temperatures and rain slow the ripening process and increase the risk of development of fungi, such as *Aspergillus*, producer of aflatoxins (Dicenta *et al*., 2003). We should note that in other *Prunus*, such as apricot or peach, development of fruits (from flowering to ripening) can become very short (70-90 days), while in some cultivars of almond like Desmayo Largueta (early flowering and late ripening), it reaches up to 220 days. Penta is the almond cultivar with the shortest cycle (130 days), due to its extra-late flowering and early maturation.

One of the great challenges we will face in almond breeding will be the resistance to pests and diseases. Navel orange worm, *Capnodis, Monilinia, Polystigma, Fusicoccum, Pseudomonas or Verticillium* will be among the most important. Resistance to pests and diseases has many advantages for producers and consumers. First of all, it reduces the production costs by eliminating or reducing phytosanitary applications, with a continuous and perpetual effect. In addition, cultivation of resistant cultivars is more environmentally-friendly and it generates healthier almonds for consumers. However, breeding for resistance presents numerous difficulties. First of all, for most of diseases we have not already identified good sources of resistance within the species, requiring the breeder to use wild related species, doing more complex and lengthy the breeding process (Gradziel *et al*., 2001). Secondly, we have no information on genetic control and transmission of resistance, so the most practical strategy would be to use resistant progenitors, assuming that the resistance is transmitted to the progeny with a high heritability. Furthermore, evaluation of resistance can be a more or less complex process depending on the pathogen. We will have to develop new methods to isolate, maintain and multiply the pathogen, as well as methods of inoculation and detection of pathogen in the plants being evaluated. Finally, we know the importance of environmental conditions on pathogen development (especially in the case of fungus), which requires the breeder to multiply their trials in different environmental conditions.

Although the breeder traditionally thought of obtaining a good cultivar, in a general way, more and more we will have to think in the creation of cultivars for each type of culture. We have already mentioned the differences between the American or Australian culture systems and most of the Mediterranean ones. These large differences show that the breeder must think if the new cultivar will be suitable for cultivation in rainfed or irrigated conditions. Under dry conditions, usually associated with a deficient culture, the resistance to drought and diseases, and the self-compatibility will be of primary importance. The less vigorous cultivars are not recommended for drought or low irrigation, as trees take longer to reach the commercial size and therefore its maximum production. This is the opposite in the new high-density plantations, where less vigorous rootstocks and cultivars are advisable, easier to control in these small frames and adapted for special harvesting machinery. These cultivars should come into bearing soon, be very productive and have an abundant branching adapted to the hedge structure. On the other hand, modern plantations, like American and Australian, where water resources and technical management of the plantation are insured, including the presence of pollinators, the main goal will remain the high productivity as a result of numerous factors related to the cultivar (abundant and stable flowering, high vigour, good performance for pruning and harvesting) and culture (water, fertilizers and diseases control).

And finally, and very important, breeders have to be aware of the consequences of the release of cultivars with poor performance or not adapted to different growing conditions. The cultivars behave differently in different regions as consequence of the environmental and culture conditions or the technical preparation of the growers. We know that several new almond cultivars have not had a good behaviour and they have been removed in a few years with the resultant loss of time and money for growers. The best cultivar is not that broadly planted, but that one that is not pulled off.

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