

## UPDATE ON BREEDING FOR RESISTANCE TO SUNFLOWER BROOMRAPE

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### SUMMARY

Sunflower broomrape (*Orobanche cumana* Wallr.) is currently regarded as one of the most important constraints in sunflower (*Helianthus annuus* L.) production. In the last fifteen years, efforts to introduce genetic sources of resistance to this parasite in sunflower hybrids have been rapidly followed by the appearance of new virulent races that have overcome all known resistance genes. Due to this situation, most of the research efforts have focused on the development and characterization of new sources of genetic resistance to the most virulent races and also to investigate the genetic structure and variability of *O. cumana* populations and their evolution in order to develop long-term strategies for sunflower broomrape management. Results of evaluation of sunflower germplasm for resistance to different races have demonstrated that wild *Helianthus* species constitute the major reservoir of genes conferring resistance to new virulent races. Cultivated germplasms are also valuable sources of resistance genes. Most of the resistant sources have been found to be controlled by major genes, although quantitative resistance and epistatic effects have also been reported. Different dominance reactions depending on the race of broomrape, the source of resistance, and the susceptible parental line used for the cross have been observed. Molecular studies have shown that phenotypic variance for race E resistance was mainly explained by a major QTL associated with the resistance or susceptibility character, while race F resistance was explained by several QTLs with a small to moderate effect, mainly associated with the number of broomrapes per plant, suggesting the existence of a quantitative component in the resistance to race F. The relevance of these findings for sunflower breeding for resistance to broomrape is discussed.

**Key words:** *Orobanche cumana*, broomrape races, genetic resistance, inheritance

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## INTRODUCTION

Sunflower broomrape (*Orobanche cumana* Wallr.) is an obligate, holoparasitic angiosperm that lives attached to the roots of sunflower (*Helianthus annuus* L.), depleting them of nutrients and water. This parasitic plant is currently regarded as one of the most important constraints for sunflower production in Southern Europe, the Black Sea region, Ukraine and China (Parker, 1994). Broomrape attacks are frequently severe and yield losses can reach up to 50% (Domínguez, 1996a). Control of this parasite remains extremely difficult, as thousands of tiny seeds produced by one single broomrape plant can be easily dispersed by wind, water, animals, humans, machinery or attached to sunflower seeds. Broomrape seeds may remain viable for 15-20 years and will only germinate in the presence of the host plant (Škorić, 1988). Although the use of herbicides is being considered as a promising control measure, at present genetic resistance offers the most effective and feasible control against *O. cumana*. However, the introduction of new resistance sources has been frequently followed by the appearance of new pathogenic races overcoming the resistance, which brings about the need for additional sources of resistance. In a classic study, Vrânceanu *et al.* (1980) identified five pathogenic races named A through E with a set of sunflower differentials carrying the dominant resistance genes  $Or_1$  through  $Or_5$ , which provide cumulative resistance to the five successive races.

In 1995, a new race (F), overcoming all the known resistance genes  $Or_1$  through  $Or_5$ , was identified in Spain and spread rapidly (Alonso *et al.*, 1996; Domínguez, 1999). Resistance to this new race was found in germplasm of both cultivated and wild sunflower (Sukno *et al.*, 1999; Fernández-Martínez *et al.*, 2000; Rodríguez-Ojeda *et al.*, 2001). However, a more virulent race (designated G) attacking the cultivars resistant to race F has been recently identified (Molinero-Ruiz and Melero-Vara, 2005). Virulent races overcoming the resistance gene  $Or_5$  were also identified in Romania in 1996 (Pacureanu *et al.*, 2004) and in Turkey, where the new races seem to be more virulent than the races present in other countries (Kaya *et al.*, 2004).

### Sources of resistance

In the early sunflower breeding work in the former USSR, sources of resistance to *Orobanche* races were found within landraces of cultivated sunflowers, but genetic resistance was also introduced into susceptible sunflower from wild species, mainly *H. tuberosus* (Pustovoit, 1966). Cultivated materials tracing back to early USSR cultivars and *H. tuberosus* were also important sources of resistance for the *O. cernua/cumana* complex of races in Romania (Vrânceanu *et al.*, 1980). Sources of resistance to recent virulent races have been scant in cultivated germplasm. Gulya *et al.* (1994) found only 22 resistant entries in a field evaluation of 903 accessions in Turkey. Domínguez *et al.* (1996) found only 8 resistant and 33

Table 1: Disease reaction of annual and perennial species to race F of broomrape

Species	Number of entries	Incidence <sup>1</sup>	DS <sup>2</sup>
Annual species			
<i>H. agrestis</i>	1	0	0
<i>H. annuus</i>	1	100	12.5
<i>H. anomalus</i>	1	0	0
<i>H. argophylus</i>	1	100	2.1
<i>H. debilis</i> (several subsp.)	3	0-35	0-1.6
<i>H. deserticola</i>	1	100	5.0
<i>H. exilis</i>	1	0-42	0-3.2
<i>H. petiolaris</i>	1	100	4.5
<i>H. praecox</i>	1	100	2.3
Diploid perennials (2n=34)			
<i>H. atrorubens</i>	2	0	0
<i>H. decapetalus</i>	2	0	0
<i>H. divaricatus</i>	3	0-10	0-1
<i>H. giganteus</i>	1	0	0
<i>H. glaucophylus</i>	1	0	0
<i>H. gracilentus</i>	1	0	0
<i>H. grosseserratus</i>	5	0	0
<i>H. maximiliani</i>	5	0-80	0-3
<i>H. microcephalus</i>	1	0	0
<i>H. nuttallii</i> (4 subsp.)	6	0	0
<i>H. salicifolius</i>	1	0	0
<i>H. smithii</i>	1	0	0
Tetraploid perennials (2n=68)			
<i>H. hirsutus</i>	1	0	0
<i>H. laevigatus</i>	1	0	0
<i>H. pumilus</i>	1	0	0
<i>H. strumosus</i>	3	0	0
Hexaploid perennials (2n=102)			
<i>H. californicus</i>	1	0	0
<i>H. ciliaris</i>	1	0	0
<i>H. × laetiflorus</i>	1	0	0
<i>H. pauciflorus</i>			
subsp. <i>pauciflorus</i>	2	0-10	0-1
subsp. <i>subrhomboideus</i>	2	0	0
<i>H. tuberosus</i>	3	0	0
Cultivated checks			
P-1380 ( <i>Or</i> <sub>5</sub> )	-	100	5.6
P-21	-	100	18.2

<sup>1</sup>Incidence=(Number of infected plants/total number sunflower plants) × 100

<sup>2</sup>DS=disease severity: average number of broomrape plants per infected sunflower plant

segregating entries in the evaluation of 429 accessions of different origins for resistance to race E, which was carried out in Spain under controlled conditions. In a more recent evaluation, only 4 entries out of 55 cultivated accessions previously reported as resistant in Turkey (Gulya *et al.*, 1994) were found to be resistant against the race F pathotypes predominant in Spain (Fernández-Martínez *et al.*, 2000). In contrast, a high level of resistance to races E and F has been found in the evaluation of wild *Helianthus* species. In Spain, Ruso *et al.* (1996) and Fernández-Martínez *et al.* (2000) found resistance to several virulent races, including race F, in 29 perennial wild species. The annual species showed a much lower level of resistance, with only four out of 18 entries evaluated showing resistance to race F (Fernández-Martínez *et al.*, 2000). Resistance to *O. cumana* has also been identified in wild *Helianthus* species in other countries (Pogorletsy and Geshele, 1976; Christov *et al.*, 1996; Škorić, 1988). All these evaluations demonstrated that wild *Helianthus* species constitute the major reservoir of genes controlling resistance to the new virulent races. Results of evaluation of wild species for resistance to the virulent race F are summarized in Table 1.

In general, transferring broomrape resistance genes from wild annual species into cultivated lines can be accomplished rather easily with a conventional crossing and backcrossing scheme. Conversely, crossing perennial *Helianthus* species with the cultivated sunflower is generally difficult due to early hybrid embryo abortion as well as high levels of sterility in the F<sub>1</sub> or BC F<sub>1</sub> generations. These problems can be overcome with the utilization of the embryo culturing technique, chromosome doubling of the F<sub>1</sub> and the creation of amphiploids (Jan and Fernández-Martínez, 2002). Using these techniques, amphiploids of the perennial wild species *H. grosseserratus*, *H. maximiliani* and *H. divaricatus*, resistant to race F, were produced and used as a bridge to transfer the resistance to cultivated sunflower (Jan and Fernández-Martínez, 2002). As a result, four germplasm populations resistant to race F, named BR1 through BR4, were developed and released (Jan *et al.*, 2002).

Although a higher frequency of resistance has been observed in wild sunflower species, some resistance to the new virulent races has been also found in cultivated germplasm, especially in material tracing back to the old Russian cultivars. From this material, four lines uniformly resistant to races B, E and F and susceptible or showing segregation for race G (Fernández-Martínez *et al.*, 2004) and three lines showing quantitative resistance to race F (Pérez-Vich *et al.*, 2005) were developed. Resistance to races F and G of broomrape has also been reported by several seed companies. A list of released lines resistant to race F from wild and cultivated origin is given in Table 2.

#### **Genetics of sunflower resistance to Orobanche and strategies of breeding for resistance**

The host-parasite system of sunflower - *O. cumana* described for races A through E appears to follow the gene-for-gene model. Vrânceanu *et al.* (1980) estab-

lished a set of five sunflower differentials carrying the five dominant resistant genes  $Or_1$  through  $Or_5$ , each giving resistance to a new race and also to the previous ones. Genetic studies carried out by other authors agreed with monogenic and dominant inheritance of resistance to sunflower broomrape (Pogorletsky and Geshele, 1976; Ish-Shalom-Gordon *et al.*, 1993; Sukno *et al.*, 1999), although two dominant genes (Dominguez, 1996b) and one recessive gene (Ramaiah, 1987) have also been reported. Genetic resistance to race F in the germplasm sources P-96 and KI-534, derived from cultivated sunflower, was found to be controlled by recessive alleles at two loci (Rodríguez-Ojeda *et al.*, 2001; Akhtouch *et al.*, 2002). These recessive genes also controlled resistance to race E in the case of KI-534 (Rodríguez-Ojeda *et al.*, 2001), while resistance to race E in P-96 was conferred by the dominant gene  $Or_5$  (Pérez-Vich *et al.*, 2004b).

Table 2: Released lines resistant to race F of broomrape

Resistant line and PI number		Origin	Pedigree <sup>1</sup>
BR1	PI 617026	Wild species; ( <i>H. grosseserratus</i> )	P-21// <i>H. gro.</i> -001/P21 (PD)/3/ HA89
BR2	PI 617027	Wild species; ( <i>H. maximiliani</i> )	<i>H. max.</i> -004/P-21(D)// P21/3/ HA89
BR3	PI 617028	Wild species; ( <i>H. divaricatus</i> )	<i>H. div.</i> -830/P-21(D)// P21/3/ HA89
BR4	PI 617026	Wild species; ( <i>H. grosseserratus</i> and <i>H. divaricatus</i> )	<i>H. div.</i> -830/P-21(D) // <i>H. gro.</i> -001/P21(D)/3/ P-21/4/HA89
P96	PI 633612	Cultivated sunflower	KREM-94-8 (Yugoslavia)
K-96	PI 633613	Cultivated sunflower	PER-94-5 (Yugoslavia)
R-96	PI 633614	Cultivated sunflower	ROD-94-15 (Yugoslavia)
L-86	PI 633615	Cultivated sunflower	Ames 3377 (VIR-115)
AM-1	PI 641057	Cultivated sunflower	VNIIMK 6540 (Russia)
AM-2	PI 641058	Cultivated sunflower	Romsun V-1352 (Romania)
AM-3	PI 641059	Cultivated sunflower	VIR 101 (Russia)

<sup>1</sup>Jan *et al.* (2002); Fernández-Martínez *et al.* (2004); Pérez-Vich *et al.* (2005)

In contrast to the resistance derived from cultivated sources, the race F resistant population BR4, derived from wild species, was found to be under the control of a single dominant gene designated  $Or_6$  (Perez-Vich *et al.*, 2002). Pacureanu *et al.* (2004) reported also a single dominant gene controlling resistance to race F in Romania. However, the results of the evaluation of crosses between different race F resistant lines and different susceptible parental lines have shown that dominance relationships and genetic control of broomrape resistance in sunflower are highly dependent on the race of broomrape, the source of resistance, and also the susceptible parental line used for the cross (Pérez-Vich *et al.*, 2004a). For example,  $F_1$  hybrids segregating for resistance and deviations from the monogenic inheritance previously reported by Pérez-Vich *et al.* (2002) were observed in some crosses between the race F resistant line J1 and susceptible lines (Velasco *et al.*, 2006).

This indicated incomplete dominance of the  $Or_6$  alleles and the presence of a second gene,  $Or_7$ , whose expression appeared to be environmentally dependent. Even though gene nomenclature  $Or_6$  and  $Or_7$  has been utilized in several different studies to designate genes that confer resistance to broomrape races superior to race E, no comparative research has been conducted and probably different loci/alleles are being reported by different authors under the same designation. A summary of different inheritance studies on broomrape resistance is given in Table 3.

Table 3: Inheritance of broomrape resistance in sunflower

Resistant source	Races tested	Genes	Gene action	References
Kruglik-A-41	A-E	$Or_1$	Single, dominant	Vrânceanu <i>et al.</i> (1980)
Jdanov 8281	A-E	$Or_2$	Single, dominant	Vrânceanu <i>et al.</i> (1980)
Record	A-E	$Or_3$	Single, dominant	Vrânceanu <i>et al.</i> (1980)
S-1358	A-E	$Or_4$	Single, dominant	Vrânceanu <i>et al.</i> (1980)
P-1380	A-E	$Or_5$	Single, dominant	Vrânceanu <i>et al.</i> (1980)
SW501	Unknown	Unknown	Single, dominant	Ish-Shalom-Gordon <i>et al.</i> (1993)
NR-5	E	$Or_5$	Single, dominant	Sukno <i>et al.</i> (1999)
R-41	E	Unknown	Two dominant genes	Dominguez (1996b)
P-96	F (Mencia; Spain)	$or_6, or_7$	Two recessive genes	Akhtouch <i>et al.</i> (2002)
P-96	E	$Or_5$	Single, dominant	Pérez-Vich <i>et al.</i> (2004b)
KI-534	E	$or_6, or_7^1$	Two recessive genes	Rodríguez-Ojeda <i>et al.</i> (2001)
KI-534	F (EK23; Spain)	$or_6, or_7$	Two recessive genes	Rodríguez-Ojeda <i>et al.</i> (2001)
J1 (BR-4)	F (Mencia; Spain)	$Or_6$	Single, dominant	Pérez-Vich <i>et al.</i> (2002)
LC-1093	F (Romania)	$Or_6$	Single, dominant	Pacureanu <i>et al.</i> (2004)
J1 (BR-4)	F (Mencia; Spain)	$Or_6, Or_7$	Two partially dominant genes	Velasco <i>et al.</i> (2006)

<sup>1</sup>The nomenclature  $Or_6$  and  $Or_7$  has been utilized by several authors, although no comparative studies have been conducted to test whether they correspond to the same loci/alleles

The development of broomrape resistant inbred lines is not an easy task, mainly because of the large difficulties to assess resistance in experimental conditions, where the existence of escapes, genetic background effects, and genotype  $\times$  environment interactions lead to a sometimes inefficient selection. Molecular studies aimed to map genes conferring resistance to races E and F have been carried out. The  $Or_5$  gene conferring resistance to race E has been mapped to a telomeric region of linkage group (LG) 3 of the sunflower genetic map (Lu *et al.*, 2000; Tang *et al.*, 2003; Pérez-Vich *et al.*, 2004b) (Figure 1). Quantitative trait loci (QTL) analyses showed that phenotypic variance for race E resistance was mainly explained by a major QTL, corresponding to the  $Or_5$  gene, associated to the resistance or susceptibility character, whereas race F resistance was explained by several QTLs with small to moderate effects, mainly associated with the number of broomrape stalks per plant (Pérez-Vich *et al.*, 2004b). These results suggested that resistance to broomrape in sunflower is controlled by a combination of a qualitative, race-spe-

cific resistance component affecting the presence or absence of broomrape, and a quantitative, non-race specific resistance component affecting the number of broomrape stalks per plant.

One important aspect in breeding for resistance to *Orobanche* is the study of the mechanisms involved in the resistance. As mentioned above, the use of resistant cultivars, usually monogenic in nature, has been followed by the appearance of new more virulent races of the parasite that overcome the existing sources of resistance. Therefore, an effective breeding strategy to achieve a more effective and durable resistance is the combination of several mechanisms in one genotype. Several groups of mechanisms of resistance to *Orobanche* have been described (reviewed by Alonso, 1998):

- Deficient production of germination stimulants released by the roots of the host plant
- Mechanical or chemical barriers preventing haustorium penetration of the host root (lignification or hypersensitive-like reaction)
- Accumulation of toxic compounds that slow down the growth of tubercles and the connection to the host vascular system

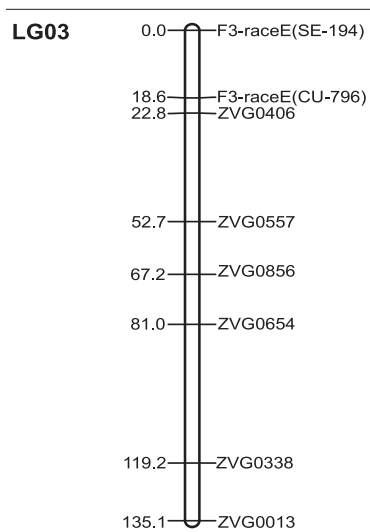


Figure 1: Molecular map of linkage group three of sunflower containing the scores for race E (populations SE-194 and CU-796) of broomrape in phenotypic evaluations of  $F_3$  populations from the cross P-21  $\times$  P-96 (Pérez-Vich *et al.*, 2004b).

Resistance mechanisms were proposed in early studies on resistance to sunflower broomrape. Resistance based on mechanical barriers was reported by Pustovoit (1966), who proposed that resistance was produced by the formation of a callus through swelling of the roots. The action of peroxidases excreted by the parasite was suggested to be involved in the lignification of host cells (Antonova, 1978). Differences in peroxidase production were suggested as an explanation of the different virulence of races A and B as well as to explain the gene-for-gene interaction in the sunflower *O. cernua/cumana* system (Antonova and Ter Borg, 1996). Different resistance mechanisms have been described for differential lines resistant to several races. For example, the mechanism of resistance of cultivar Jdanov 8281 carrying the *Or*<sub>2</sub> gene was reported to include a hypersensitive-like reaction (Antonova and Ter Borg, 1996), while the accumulation of phenolic compounds in damaged cells and lignin formation in sunflower vessels were reported to be involved in the resistance controlled by the gene *Or*<sub>3</sub> (Tolmachev, 1991). More recently, Labrouse *et al.* (2001) and Echevarría-Zomeño *et al.* (2006) compared resistant and susceptible sunflower genotypes and

identified several resistance mechanisms such as reduced stimulation of broomrape seed germination, suberization and protein cross-linking in the cell wall in contact with the parasite, and secretion of phenolic compounds that poisoned the parasite.

## CONCLUSIONS AND FUTURE PROSPECTS

The rapid evolution of *O. cumana* populations leading to the appearance of new virulent races requires a continuous search of new resistance sources. Results of evaluation of sunflower germplasm for resistance to different races have demonstrated that wild *Helianthus* species constitute the major source of resistance genes conferring resistance to new virulent races, but cultivated germplasms are also valuable sources of resistance. Most of the resistant sources have been found to be controlled by major genes (vertical resistance), although quantitative (horizontal) resistance has also been reported. Race-specific dominant genes are considered the ideal source of resistance for single-cross hybrid breeding by seed companies, because they only need to be incorporated into one of the parents. However, the combination of vertical and horizontal resistance mechanisms on the same genotype could contribute to the development of a more durable resistance. Molecular marker studies to identify QTLs associated with broomrape resistance genes are increasingly contributing to clarify the genetic control of broomrape resistance in sunflower, to facilitate the pyramiding of different resistance genes, and to speed up the development of resistant inbred lines through marker-assisted selection.

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## ACTUALIZACIÓN DE LA SITUACIÓN DE LA MEJORA GENÉTICA DE GIRASOL PARA RESISTENCIA AL JOPO

### RESUMEN

El jopo de girasol (*Orobanche cumana* Wallr.) está considerado en la actualidad como uno de los problemas más importantes del cultivo de girasol (*Helianthus annuus* L.). En los últimos quince años, los esfuerzos realizados para incorporar fuentes de resistencia genética a este parásito en híbridos de girasol han estado acompañados por la rápida aparición de nuevas razas virulentas que superaban todos los genes de resistencia conocidos. Debido a esta situación, la mayoría de los esfuerzos de investigación se han centrado en el desarrollo y caracterización de nuevas fuentes de resistencia genética a las razas más virulentas del parásito, así como en la investigación de la estructura genética y variabilidad de las poblaciones de *Orobanche cumana* y de su evolución, con el objetivo de desarrollar estrategias duraderas a largo plazo para el control del jopo de girasol. Los resultados de evaluación de germoplasma de girasol para resistencia a diferentes razas han demostrado que las especies silvestres de *Helianthus* constituyen la mayor fuente de genes de resistencia a las nuevas razas virulentas. El germoplasma cultivado es también

una valiosa fuente de genes de resistencia. La mayoría de las fuentes de resistencia están controladas por genes mayores, pero tanto resistencia cuantitativa como efectos epistáticos han sido también identificados. Se han observado diferentes reacciones de dominancia dependiendo de la raza de jopo, la fuente de resistencia y la línea utilizada como parental susceptible. Estudios moleculares han mostrado que la varianza fenotípica para la raza E se explica principalmente por un QTL mayor asociado con la resistencia o susceptibilidad del carácter, mientras que la resistencia a la raza F estuvo controlada por varios QTL de efecto pequeño o moderado asociados principalmente con el número de jopos por planta, lo que sugiere la existencia de un componente cuantitativo en la resistencia a la raza F. Se discute la relevancia de estos resultados en la mejora para resistencia al jopo de girasol.

