

## Broomrapes (*Orobanche* spp.) the Challenge and Management: A review

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Received on 1/7/2021 and Accepted for Publication on 29/8/2021.

### ABSTRACT

Broomrapes (*Orobanche* spp.) are among the most damaging parasitic weeds to agriculture. The subsite themselves on the roots of a wide range of cultivated and wild-grown plant species of different plant families. These parasites are varied in morphology and plant hosts they attack, although they share a large number of host species. Certain *Orobanche* species are more specialized to plant species of specific growth forms such as fruit and forestry trees. All *Orobanche* species are obligatory parasites because they lack chlorophyll and thus heterotrophic completely depend on host plants for food and/or water absorbed through specialized organs called a haustoria. The present review introduces information on biology, ecology, distribution, host/parasite relationship, economic importance, and management of the most important *Orobanche* species widely spread in Jordan and worldwide that cause great yield loss of different economic crops and devastate yield totally under heavy infestation. Recent literature and overview information on methods of control followed in Jordan and different parts of the world are included and discussed.

**Keywords:** Parasitic weeds, *Orobanche* spp., Broomrapes, host species, managements

### INTRODUCTION

Orobanchaceae is mainly a northern warm and temperate zones family. *Orobanche* spp. is reported from more than 58 countries. The family Orobanchaceae consists of 89 genera including 2061 species (Nickrent, 2008; Gevezova *et al.*, 2012). The majority of species are facultative or obligate root parasites that subsist on broad-leaf plants, and exhaust hosts' nutrients, minerals, and water. The main representative genus is *Orobanche*, a destructive root parasite that includes more than 160 parasitic species of most crop destructive and problematic species are branched broomrape (*O. ramosa*), Egyptian broomrape (*O. aegyptiaca*), nodding broomrape (*O. cernua*), crenate broomrape (*O. crenata*) and small broomrape (*O. minor*); some workers add the sunflower

broomrape (*O. cumana*) and fetid broomrape (*O. foetida*) (Parker, 2009). The main hosts of these parasites are species of Leguminosae, Apiaceae, and Asteraceae for *O. crenata*, sunflower (*Helianthus annuus*) for *O. Cumana*, Solanaceae for *O. cernua*, Leguminosae for *O. foetida*, clover (*Trifolium* spp.), and alfalfa (*Medicago sativa*) for *O. minor*, and many families, including the Solanaceae, Cucurbitaceae, and Brassicaceae for *O. ramosa* and *O. aegyptiaca* (Qasem, 2009; Parker, 2012; Punia, 2014). Different *Orobanche* species may also attack species of different plant families. *Orobanche minor* was reported to parasitize plants from at least 16 orders of monocots and dicots (Thorogood *et al.*, 2009). Parasite shoot/s appear above the soil almost at the

end of its life cycles and only for flowering and seed production (Fernández-Aparicio *et al.*, 2016).

*Orobanch* spp. is holo-parasites, annual in duration, prolific seed producers, seeds are tiny measuring 0.2 by 0.3mm, with a minute amount of reserved food. A single shoot produces 270.000 seeds that are widely disseminated by wind and survive in the soil for 20 to 30 years.

Differences exist between species in flower and seed size, flower color, and other morphological variations.

### GERMINATION AND DEVELOPMENT

*Orobanch* seeds must undergo a period after ripening which may extend for 18-24 months, followed by a conditioning period, before responding to germination stimulants. Some chemicals can shorten this period (Song *et al.*, 2005) enhance the response of *Orobanch* spp. seeds to the artificial germination stimulant GR24 (Song *et al.*, 2006).

Seeds germinate when became close to or in contact with host roots, but are triggered by receiving host germination stimulants through root exudates. The optimal temperature for germination is 20-25°C and 20/10°C for attachment. Light enhanced *O. ramosa* germination but inhibited germination of *O. crenata*, pH, calcium, or phosphate ions affect germination stimulants and microbes inactivate stimulants in the soil. Some nonhost root exudates, ethylene, gibberellic acid, and calcium hypochlorite enhance parasite seed germination (Qasem, 2006a).

### CONTACT AND ATTACHMENT

*Orobanch* germinated seed extends a radicle (germination tube) that moves toward the host root system in a chemotropic response or bending movement in response to inhibitory chemicals in the host root exudates. Successful contact needs the radical locates host root, haustoria development, penetration into the host root, and connection between vascular systems of the parasite and host plant. Upon the contact sticky papillae adhere the parasite to the host root surface. Penetration occurs mainly by mechanical pressure on the host cells and hydrolytic enzymatic action

(Veronesi *et al.*, 2007). The primary haustoria and the tubercles are the major connecting organs. After attachment, the radicle doesn't act anymore. The haustoria swell forms tubercles or nodules and connect with the vascular system of host plants and s absorption of the required materials. The parasite functions as a powerful super sink strongly deprive water, mineral nutrients, and carbohydrates. *Orobanch* accumulates mannitol that lowers parasite osmotic potential much more negatively than the host. Upon haustorial growth, an underground tuber develops, shoot bud differentiates, elongates, and emerges above the soil only for flowering and seeding.

*Orobanch* seedlings have no chlorophyll and in absence of a suitable host, they soon shrivel and die. the life cycle of the parasite involves two phases, the conditioning start, important for leaching germination inhibitors from parasite seeds and germination stimulates or related substances are accumulating, and the second phase is seedling attachment to the host root system and the start of true parasitism. The latter phase is further divided into the hypogeal stage occurs below the soil level and the epigeal stage during which the vegetative organ grows rapidly and produces reproductive organs above the soil. Emergence, flowering, and seeding of the parasite may take 15 to 18 days.

### ECONOMIC IMPORTANCE

*Orobanch* spp. are problematic and destructive parasites to agriculture in different parts of the world and difficult to control (Rubiales and Fernández-Aparicio, 2012; Habimana *et al.*, 2014; Fernández-Aparicio *et al.*, 2016). They attack a large number of cultivated and wild species (Parker and Riches, 1993; Qasem, 2009) and can totally destroy crops under heavy infestation. (Jain and Foy, 1992; Fernández-Aparicio *et al.*, 2016).

*Orobanch crenata* and *O. ramosa* are the most common and cause yield loss of more than 75% (Kamel, 2005). In the Mediterranean and West Asia, about 16 million ha has been reported as threatened. Yield loss was estimated at hundreds of millions of dollars annually affecting the life of 100

million farmers. Aly (2007) reported annual losses estimation in food crop caused by *Orobanche* spp. in the Middle East at billion dollars. Under heavy infestation, crop yields may be completely lost (Barney *et al.*, 2005; Qasem, 2019 and 2020a) especially in marginal areas or in dry regions (Silverside, 2002a, b; Barney *et al.*, 2005).

*Orobanche cernua* severely attacks tomato, tobacco, and sunflower. Yield loss in tobacco ranges from 30 - 70% (Dhanapal, 1996), affects yield and quality and heavy infestations destroy 25% of the crop in India (Mariam and Suwanketnikom, 2004) and is exhaustive to beans (*Phaseolus* sp.) in Italy. *Orobanche* causes considerable yield losses in tobacco, clover, tomatoes (*Lycopersicon esculentum* Mill.), sunflowers, and broad beans (*Vicia faba* L.) in the USA (Ristau, 2001). Yield losses due to *O. crenata* may reach as high as 75-100% in certain parts of the Sudan and Ethiopia (ICARDA, 2006) while seed-yield losses caused by *O. foetida* in broadband reached 95% (Bouraoui *et al.*, 2016).

*Orobanche* species may also serve as hosts or carriers for viruses, bacteria, and polyphagous insects. *Orobanche ramosa* L. was mentioned as a new host for *Pseudomonas syringae* PV. Tomato (Nevena and Senka, 1997) and has been reported as a novel host that facilitates replication and processing of viroids such as PSTVd (Vachev *et al.*, 2010).

## CONTROL.

Different strategies have been proposed for *Orobanche* spp. control (Rubiales and Fernández-Aparicio, 2012; Punia, 2014; Fernández-Aparicio *et al.*, 2016; Samejima and Sugimoto, 2018) including prevention; agricultural such as planting date, crop rotation with trap and catch crops (Al-Menoufi, 1991), nitrogenous (Jain and Foy, 1992) and mineral fertilizers and managed fallow; physical methods such as the use of soil plastic mulch, soil solarization with or without animal manure fermentation, flooding, organic material, and burning; breeding for resistant cultivars (Foy *et al.*, 1988; Cubero and Hernandez, 1991; Qasem and Kasrawi, 1995); mechanical including hand weeding,

weeding after harvest and deep plowing; biological using insects and fungi (Parker and Riches, 1993) such as *Fusarium oxysporum* (Cubero *et al.* 1999; Lu *et al.* 1999; Thomas *et al.* 1999a,b); and chemical control methods using soil fumigants (Foy *et al.*, 1989), germination stimulants (Qasem, 2006b) and herbicides.

In the last two decades, sulfonylurea and imidazolinone herbicides were introduced for parasites control in tomatoes and results have been reported on selective control of *O. aegyptiaca* by chlorsulfuron and triasulfuron (Ghannam *et al.*, 2012) and *O. ramosa* by chlorsulfuron (Qasem, 1998). Persistence, toxicity, and low selectivity of these and imidazolinones with the high cost and public concern on human health and environment necessitate the search for alternatives. Genetic engineering has also been proposed. However, complete control methods are not yet available (Qasem, 2006a; Rubiales and Fernández-Aparicio, 2012; Habimana *et al.*, 2014; Disciglio *et al.*, 2016; Fernández-Aparicio *et al.*, 2016). Below are details on methods employed for *Orobanche* spp. control.

## Prevention Methods

*Orobanche* seeds spread by different means from contaminated crop seeds to the workers (Qasem, 2006b). Prevention is an important approach, i.e., sowing clean washed crop seeds. Contaminated containers should not be used and prevention of parasite seeds dispersal between fields is necessary (Kebede and Ayana, 2018). National and international trade of crop seeds should be strictly subjected to quarantine regulations. Prevention of animals feeding on parasitic weeds or controlling their movement. *Orobanche ramosa* subsp. *mutelii* (F.W. Shultz) Cout. was reported to transmit by sheep wool or by pass-through gastrointestinal tract (Ginman *et al.*, 2015). In addition, it is important to eradicate parasitic weeds in newly infested fields. Hand weeding and burning of parasite shoots is necessary to prevent seed spread and control of weeds in general during fallow years and before seeding is needed to prevent parasitic weed on wild or weed species.

### Cultural and Mechanical Methods

These include:

#### Land Preparation

Deep plowing was proposed for *O. ramosa* in tomato (Labrada and Perez, 1988) and *O. cernua* in tobacco (Khot *et al.*, 1987). Zero and minimum tillage increased broad band infestation by *O. crenata* (Kukula and Masri, 1984) and perennial weeds while 40-50 cm deep tillage reduced *Orobanche* by 80-90% in three year-period (Cited by Kasasian, 1971).

#### Planting or Sowing Date

Van Hezewijk *et al.* (1987) and Raaimakers *et al.* (1988) confirmed severe infestation of early plantings of broadbean and lentil by *O. crenata*. Munoz *et al.* (1993) reported that the emergence period of *O. cernua* increased as the sowing date was delayed. Sunflower yield was higher at earlier sowing dates and may be recommended in *Orobanche*-infested areas under mild Mediterranean climate. Germination of *O. crenata* tends to be zero below 8°C. Delaying the planting date affects *Orobanche* more than its hosts (Habimana *et al.*, 2014). For effective control of *O. crenata*, broadbean cv. Giza 402 should be sown around mid-November in Egypt without glyphosate application and with zero tillage (Nassib *et al.*, 1984). Early sowing of peas was effective in reducing *Orobanche* incidence (Pirani *et al.*, 1993). However, the change of sowing date seems not highly promising under certain conditions. *Orobanche cumana* on sunflower appeared earlier at late than early planting dates. *Orobanche* shoots per plant were fewer when sunflower planting was late (Aydin and Mutlu, 1996). In another study, parasitism of *O. crenata* was decreased with later sowing dates, while better results were obtained with resistant varieties and late sowing (Sillero *et al.*, 1999). Perez-de-Luque *et al.*, (2001) came also to the same conclusion.

#### Planting Depth

The position of *Orobanche* seeds in the soil plays a major role in determining parasitism. Mohamed-Ahmed and

Drennan (1994) reported significant failure in *O. ramosa* emergence when crop plants were grown from seeds planted at 11-cm or deeper compared with seeds planted at 3-4 cm depth. Eltayeb *et al.* (2000) found that *O. ramosa* seeds placed 10 cm deep resulted in heavy infestation compared to those placed at 15 cm thus tomato seedlings planted at 15 cm, reduced parasite infestation.

#### Hand Weeding

An option available to farmers worldwide and cheap in populated poor societies. Hand-pulling of *O. cernua* in tobacco resulted in almost complete control after 3 years (Krishnamurthy and Rao, 1976). Clean cultivation followed by hand weeding or hoeing was commonly recommended for *Orobanche* control and systematically before flowering for several years until exhaustion of the seed bank (<http://www.wssa.net/subpages/weed/larrymitich/Orobanch e.html>). Weeding of the parasites is not very promising in heavily infested areas, is time-consuming, tedious, only workable at a long-term practice, and can cause injuries to the root system. However, it is an important tool of control, in fields with starting infestation and when repeated 3-4 times a season at 4-5 days intervals was effective in eradicating the parasite within 5-6 years (Krishnamurthy, 1992).

#### Crop Rotation with Trap/Catch Crops

##### Trap Species

Cultural methods usually involve the inclusion of trap or catch crops in rotation. Crop rotation with non-host crops especially with trap species is of great advantage (Eltayeb *et al.*, 2000). Schnell *et al.* (1994) reported legume crops to cause a great reduction in *O. crenata* seed banks and resistance has been found both in cultivated and wild grown legumes (Rubiales *et al.*, 1999) including different *Lathyrus* spp. which may be used as trap crops (Sillero *et al.*, 2001).

Trap species is a false host that stimulates parasite seed germination but is not parasitized. It exhausts the parasite seed bank in integration with other methods of parasite management while traps species or stimulatory natural

chemicals (Yoneyama *et al.*, 1998a,b; Evidente *et al.*, 2010; Daniel *et al.*, 2011) may be incorporated in parasite management. Sunhemp (*C. juncea* L.) and green gram (*Vigna radiata* L.) are promising trap crops in bidi tobacco. Peppers (*Capsicum annuum* L.) in rotation with tobacco to reduce broomrape seed infestations (<https://wssa.net/wp-content/themes/WSSA/WorldOfWeeds/orobanche.html>) and pepper roots stimulated germination of 22-26% of nodding *Orobanch* seeds with no attachments. In pepper intercropping with tomato, a Four-fold increase in the number of nodding *Orobanch* was observed on tomato roots compared with the number of parasites on tomato roots planted separately. *Vicia villosa* subsp. *Da Scarpa* in rotation with lentil, chickpea, and broad bean kept *O. crenata* infestation at a low level (Schnell *et al.*, 1996). Flax (*Linum usitatissimum* L.) in two successive winter seasons or one summer cropping with *Phaseolus aureus* Roxb. (*Vigna radiata*) reduced early infestation of *O. aegyptiaca* and significantly increased tomato growth and production (Kleifeld *et al.*, 1994). Coat buttons (*Tridax procumbens* L.), and hairy beggar-ticks (*Bidens pilosa* L.) have been also reported to reduce parasite infestation (<http://www.wssa.net/subpages/weed/larrymitich/Orobanch e.html>).

Some highly successful species in rotation included sesame, brown Indian hemp, common flax, and black-eyed pea (*Vigna unguiculata* (L.) Walp.) that reduced broomrape biomass and increased tomato yield. Sesame, brown Indian hemp, Egyptian clover, and mungbean increased tomato biomass (Babaei *et al.*, 2010). Flax was most effective and reduced *O. crenata* in lentil fields. Flax and sugarcane significantly reduced *O. crenata* in a rotation with broad bean (Abou-Salama, 1995). Broccoli reduced the shot number of the same parasite species by 48% and 39% in two years (Aksoy *et al.*, 2016). Different species stimulated seed germination of *Orobanch* spp. by more than 90%, and extracts of many plant species may be considered as a trap, cover, catch species, or a source of natural germination stimulants for these parasites (Babaei *et al.*, 2010; Ma *et al.*,

2012; Qasem, 2019). However, heavily infested fields should be planted with trap species for 2 or 3 years to exhaust the parasite seed banks.

Different cultivated or wild species with great potential to stimulate *Orobanch* seed germination have been reported including sorghum (*Sorghum vulgare* Pers.), barley (*Hordeum vulgare* L.), and vetch (*Vicia dasycarpa* spp. *villosa*) for *O. crenata* (Linke *et al.*, 1991); bean, sorghum, maize, and cucumber for *O. ramosa* (Labrada and Perez, 1988) and sorghum, cowpea, chili, hemp, mung bean, flax, lucerne, soybean and chickpea for *O. cernua* (Krishnamurthy and Rao, 1976; Krishnamurthy *et al.*, 1977) while flax was the most potent trap crop. Linke *et al.*, (1991) showed a significant reduction in *O. crenata* infestation after three years of growing *V. dasycarpa* spp. *villosa*. Forage legumes have been recommended as trap crops to reduce broomrape's seed bank (Saxena *et al.*, 1994). Sillero *et al.*, (2001) reported the possible use of *Lathyrus choranthus* as a trap crop since permitted a very low emergence of broomrape shoots but allowed a relatively high establishment of the parasite with low susceptibility to *Orobanch*.

The non-suitable host crops of *O. cernua* including chili, sorghum, cowpea, *Phaseolus aconitifolius*, and *Hibiscus sabdariffa* L. stimulated germination of the parasite at a high level. Sesame (*Sesamum indicum* L.) stimulated germination but without offering further growth and development (Krishnamurthy and Chandwani, 1975). Root diffusate of *L. usitatissimum*, *C. annuum*, *S. indicum*, and *Trifolium alexandrinum* L. enhanced *Orobanch* seed germination, but the germinated seeds failed to attach to their root systems (Krishnamurthy *et al.*, 1977; Al-Menoufi, 1991). Strong induced germination of *O. cernua* seeds was obtained using *V. radiata* and *C. juncea* (Dhanapal *et al.*, 1998). Boulet *et al.*, (2001) reported *Avena sativa* ssp. *sterilis*, *Ammi majus*, *Solanum nigrum*, and *Anagallis arvensis* possessed different levels of resistance that led to the death of *O. ramosa*. Rodriguez-Ojeda *et al.* (2001) found that corn, sorghum, millet, cotton, rice, eggplant, and cauliflower stimulated germination of *O. cumana* seeds.

*Avena* was reported as a germination stimulant from *Avena strigosa* (Kim *et al.*, 2014). Zemrag and Bajja (2001) reported fenugreek and coriander reduced the number of attached parasites per host plant and disturbed their development.

Maize and snap bean as traps for *O. ramosa* under intercropping, depleted the seed bank of *O. ramosa* and *O. cernua* by 72.5% per season (Abebe *et al.*, 2005), and significantly increased tomato yield. Dongola (2006) reported that rotation of tomato with onion reduced *O. ramosa* infestation by 90-95% and increased tomato yield by 60%. Qasem (2019) found that the highest *O. ramosa* shoot number was found on tomato followed by *Anethum graveolens* L., *C. vulgaris*, *Cucumis melo* var. *flexuosus* L., *Pimpinella anisum* L., *S. indicum*, *Solanum elaeagnifolium* Cav., *S. vulgare*, *Spinacia oleracea* L., and *T. alexandrinum* but lowest after *Brassica oleracea* L. var. *Italica* plenck, *Brassica rapa* L. var. *Rapa*, *C. annuum*, *Capsicum frutescens* L., *Cicer arietinum* L., *Citrullus colocynthis* (L.) Schrad., *Cucurbita maxima* Duch., *Cuminum cyminum* L., *H. vulgare*, *L. usitatissimum* L., *Spinacia oleracea* L. cv. *Epinard* greant and *Vigna sinensis* (L.) Savi. Parasite dry weight per shoot was lowest on tomato grown after *C. arietinum*, *C. frutescens*, *Cucumis melo* L., *H. sabdariffa*, *P. anisum*, and *T. alexandrinum* but highest after *Cichorium endivia* L. var. *crispum* Lam., *Peganum harmala* L., *S. oleracea* cv. *Epinard* greant and *Zea mays* L. Tomato shoot dry weight increased by 126% over parasite-free control following *Ecballium elaterium* (L.) A. Rich. and parasite infestation reduced by 56% of the *Orobancha*-infested control. High tomato growth and best parasite control (73% reduction) were obtained after *V. sinensis*, *H. sabdariffa*, *H. vulgare*, and *S. vulgare* reduced both *Orobancha* infestation and tomato growth.

Trap crops may effectively reduce *Orobancha* seed bank, and could be used as a part of an integrated *Orobancha* control approach. Good results with effective trap crops may not be efficient, possibly not practicable for ecological/economical reasons. Development of the parasite on weeds needs to be eliminated, while important trap crops

to reduce the seed bank for different parasitic weeds are not available. The success of trap crops in the exhausting soil seed bank of the parasite may be highly questionable under severe infestation or require a fairly long period for effective control which may not be economically feasible in certain growing systems.

### Catch Species

These are true hosts that induce parasite seed germination and parasitized. They are infected or enhanced parasite seed germination and attachment but hinder its development by mechanical, physiological, or chemical factors. These must be sacrificed, harvested, plowed, or destroyed after 6-8 weeks, mostly at vegetative and before parasite emergence or latest before parasite flowering. Catch crops are likely used as preceding crops and have to be closely planted. This method of control, however, is costly because of additional labor, is not usable if the growing season is short, and needs good mechanization because of the possible loss of a growing period. However, cultivation of all hosts should be easy and inexpensive, germination stimulation should be high, their elimination is not problematic, and they are as high in yield as fodder or green manure. Acharya *et al.*, (2002) reported that two successive crops of toria (*Brassica campestris* var. *toria*) reduced *O. aegyptiaca* seed bank by 20.9% and 26.2% for both crops, respectively. The optimum density of toria plants required for significant reduction of *O. aegyptiaca* seed bank was about 140 plants/m<sup>2</sup>.

### Intercropping with Trap or Catch Species

Al-Menoufi and Adam (1998) concluded possible use of *Trigonella foenum-graecum*, *Lupinus termis*, *Coriandrum sativum*, and *Brassica rapa* L. in intercropping with broad bean or tomato to reduce *Orobancha* on host roots. Many of these crops, however, were found attacked by *O. ramosa* (Qasem and Foy, 2007). Abbes *et al.* (2019) reported that intercropping with fenugreek enhanced seed yield and reduced *O. foetida* infestation in the broadbean. Inhibition of *O. crenata* seed germination by allelochemicals released by

fenugreek roots was suggested as the mechanism for the reduction in parasite infection (Fernández-Aparicio *et al.*, 2008c). The use of a variety of mixtures of plant species is considered as a possible strategy to affect Orobanche-host interaction by combining certain host species with different degrees of susceptibility (Bouhatous and Jacquard, 1994). Experimentation in Egypt reported a significant reduction of *O. crenata* infection on broad bean and pea inter-cropped with berseem clover. Mini-rhizotron experiments demonstrated reduction in *O. crenata* infection on pea, lentil and chickpea (Fernández-Aparicio *et al.*, 2010a).

Garlic in peas resulted in the least Orobanche emergence, while higher seed yield was obtained when peas were mixed with onion. Complete elimination of Orobanche emergence was achieved in a mixture with black cumin (Hassan, 1998). Maximum germination of *O. cernua* was obtained when the parasite seeds were exposed to the green gram, sun hemp, and sesamum followed by black gram and sunflower (Dhanapal *et al.*, 1998). *Arabidopsis thaliana* induced seed germination of *O. aegyptiaca*, *O. minor*, and *O. ramosa* at a rate of 87, 72, and 67% of maximum seed germination, respectively (Goldwasser *et al.*, 2000). Root exudates of corn, sorghum, millet, cotton, rice, eggplant, and cauliflower induced seed germination of *O. cumana* under laboratory conditions, and none was infected (Rodriguez-Ojeda *et al.*, 2001).

Certain weeds include *Avena sterilis*, *Conyza canadensis*, *Ammi majus*, *Datura stramonium*, *Cichorium endivia*, *Anagallis arvensis*, and *Solanum nigrum* supported *O. ramosa* attachment but different resistance levels were observed and led later to the death of the parasite (Boulet *et al.*, 2001). These authors suggested using these weeds as trap species for *O. ramosa* control. Qasem and Foy (2007) screened a large number of weed species for infection with *O. ramosa* and found many were heavily infected and others were nonhosts. However, a wide variation in tomato infestation was observed when was planted after these weeds. Orobanche *crenata* infection on broad bean and pea was reduced when intercropped with oat. Pot and rhizotron

experiments confirmed the reduction of infection in faba bean intercropped with cereals. The inhibition in seed germination by allelochemicals released by cereal roots is the mechanism for the reduction of *O. crenata* infection (Fernández-Aparicio *et al.*, 2007). Fernández-Aparicio *et al.* (2013) reported inhibition of *O. crenata* seed germination and radicle growth by cereals allelochemicals. Intercrops with oat (*A. sativa* L.), fenugreek (*T. foenum-graecum*), or berseem clover (*T. alexandrinum*) can reduce *O. crenata* infection on legumes because of allelopathy influence (Fernández-Aparicio *et al.* 2008b, c, 2010a). Parasite seed germination was inhibited in presence of oat or fenugreek roots suggesting the release of toxic substances. Trigoxazonane in fenugreek (Evidente *et al.* 2007) or benzoxazolinones (Fernández-Aparicio, unpublished) from oat root exudates may be responsible for the inhibition obtained.

Intercropping of canola with wheat could significantly reduce *Phelipanche aegyptiaca* growth depending on the type of wheat genotype. The inhibitory potential of wild wheat genotypes was stronger than cultivated genotypes (Razavifar *et al.*, 2017). However, the success of trap crops may be highly questionable under severe infestation or may require a fairly long period for effective control which may not be economically feasible under certain growing systems.

#### Plant Residues and Soil Cover

Surface applied and pre-plant incorporated wheat and barley straw mulch residues significantly reduced *O. ramosa* infestation and growth in potatoes (Haidar *et al.*, 1995a). Olive cake for Orobanche spp. control on different crops has been also reported (Ghosheh *et al.*, 1999, 2006; Aybeke, 2016, Disciglio *et al.*, 2016; 2018). Peas were not infected with *O. crenata* in the olive cake-containing media at any parasite inoculation density while the sporadic infection was detected on faba bean and tomato in media inoculated by *O. crenata* and *O. lavandulacea* on both crops, respectively. Aybeke (2016) found that olive cake composting achieved success against *O. cernua* in sunflower and was suggested to

improve and provide regular plant development in arid lands of intense *Orobancha* infestation. Disciglio *et al.*, (2016) tested 12 agronomical, chemical, biological, and biotechnological strategies for *Phelipanche ramosa* (L.) Pomel control in processing tomato but none provided complete control of the parasite. Later Disciglio *et al.*, (2018) reported olive mill wastewater as effective against *Ph. ramosa* infestation and increased tomato productive parameters.

Qasem (2020) reported effective control of *O. ramosa* in potted tomato using olive mill wastewater and olive cake but the first was more selective and effective against the parasite. Qasem (2002), reported high allelopathic activity of shoot residues of certain weed species and root exudates of different weed and crop species on seed germination of *O. ramosa* in tomato grown under glasshouse conditions.

### Soil Mulch and Solarization

Soil solarization is a nonselective method that works against all weeds including *Orobancha* spp. and soil pests. Plastic mulch was found effective in controlling *Orobancha* sp. (Tsybul'skaya and Skoklyuk, 1978). Only soil solarization has eliminated *Orobancha* and the majority of weeds from the treated plots. The yield has increased from 7.8 t/ha of untreated control plots to 21.08 t/ha on plots treated with solarization (Abdalla and Dabrowski, 2000). *Orobancha aegyptiaca* was controlled with solar heating using polyethylene clear film 0.03 mm thick left in place for 30-50 days in the summer (Cartia, 1985). The efficacy of this technique, however, may be improved when combined with organic supplementation, with positive effects on the yield of greenhouse tomatoes. Solar heating followed by mulching was promising for the control of *O. ramosa* and increased eggplant yield with glyphosate used at 40g/ha (Braun *et al.*, 1985). Sauerborn and Saxena (1987) obtained corresponding results against *O. crenata* in faba bean and lentil in Syria, 40 days' treatment lead to > 90% control in both crops; and similarly Abdel-Rahim *et al.* (1988) controlled *O. crenata* in faba bean in Egypt by 10 weeks treatment. Soil solarization

reduced the population and incidence of *Orobancha* (Sauerborn *et al.*, 1989). Black plastic mulch completely controlled *O. ramosa* and *O. aegyptiaca* in tomato and eggplant (Vouzounis and Amerikanos, 1998). It was also effective in controlling *O. cernua* in tobacco (Meti and Hosmani, 1994), and *O. crenata* in broad bean (Abdalla, 1999).

Soil solarization killed *Orobancha* seeds at 0 cm depth, but in combination with chicken manure seeds at soil depths from 0-10cm were killed (Haidar and Sidahmed, 2000). Solarization for 2-6 weeks with or without chicken manure significantly reduced weed growth and infestation in cabbage. Pre-plant composting with fresh manure under plastic mulch in the planting rows causes *Orobancha* seeds to lose viability within six weeks and reduced *O. ramosa* infestation on many vegetables. Two consecutive years of soil solarization are needed under the Mediterranean conditions to completely eradicate the broomrape seed banks in highly infested soil (Mauro *et al.*, 2015). There is a residual effect over several years following this treatment, resulting in increased crop yields. This method, however, is not applicable in general for economic reasons, but under certain conditions, where water is available for irrigation.

### Mineral Fertilization/Organic Matter

*Orobancha* tends to associate with less fertile soil conditions. High levels of chicken manure and fertilizer, especially nitrogen, have a suppressive effect. Nitrogen fertilizer reduced *O. crenata* (Kukula and Masri, 1984). Ammonium nitrate alone or in combination with potassium phosphate completely inhibited infection of tomato by *O. aegyptiaca* (Jain and Foy, 1987). Ammonium nitrate with potassium phosphate or ammonium phosphate alone was most effective in reducing parasitism and enhancing the growth of tomato plants in *O. aegyptiaca* infested fields (Mariam and Suwanketnikom, 2004). Low rates of ammonium sulfate reduced *O. crenata* infestation without hurting *V. faba* (Jain and Foy, 1992). Ammonium-N-based liquid fertilizer in direct contact with *O. crenata* adversely



affected parasite germination potential. The effect was dependent on the rate of N-used (Eplee *et al.*, 1994). The number of the emerged and dry weight of *O. ramosa* in tomatoes decreased with an increase in N level, while an increase in the level of K had an opposite effect (Demirkan and Nemli, 1994).

Ammonium sulfate (8mM) applied during the conditioning period reduced germination of *O. crenata*, 4mM ammonium sulfate strongly inhibited germination when applied after conditioning during the germination phase. Urea (8mM) reduced germination to a limited extent (Van Hezewijk and Verkleu, 1996). Radicle lengths of *O. aegyptiaca* and *O. ramosa* were inhibited by ammonium nitrate and ammonium chloride than by potassium nitrate and both parasite species were different in their sensitivity to nutrients (Nandula *et al.*, 1996). Ammonium form was more inhibitory to *Orobancha* spp. than nitrate (Westwood and Foy, 1999). Germination of *O. aegyptiaca* and *O. oxyloba* was strongly inhibited by copper and vanadium, while boron inhibited radicle elongation of *O. oxyloba* at 25ug/liter (Zaitoun *et al.*, 1996) and foliar spray of 0.5% boric acid 60 days after *V. faba* sowing completely controlled *O. crenata* (Hassan and Farrag, 1982). Elongation of *O. aegyptiaca* and *O. oxyloba* was inhibited by Zn and Mo (Zaitoun *et al.*, 1996). In potatoes, chicken manure alone or with sulfur was effective in reducing *O. ramosa* growth and infestation early in the season. The mixtures of chicken manure and sulfur at 8 and 12 t/ha significantly reduced late *Orobancha* infestation in eggplant (Haidar and Sidahmed, 2006).

### **Flooding**

Soil flooding for weeks killed parasite seeds in the soil (Goldwasser and Rodenburg, 2014). Under rainfed agriculture, water shortage usually could not permit this method. Regular irrigation will support the host to compensate for the attack of the parasite to a certain extent. However, water lodging inhibited *Orobancha* emergence when applied for more than 6 weeks (Mohamed-Ahmed and Drennan, 1994).

### **Resistant and Tolerances**

The most outstanding are sunflower varieties resistant to *O. cernua*/Cumana but resistance has often been overcome by new, more virulent 'races' of the parasite in many countries.

Sauerborn *et al.* (2002) induced resistance in sunflower against *O. cumana* using benzo (1,2,3) thiadiazole-7-carbothioic acid S-methyl ester (BTH), the active ingredient of Bion®, under controlled growth chamber conditions. In sunflower, the parasite was effectively controlled using two resistant hybrids, Favorite (Ypsilon S.A.) and Odil (Pioneer) (Syka and Economou, 2005).

Sunflower cultivar M15 from Argentina showed complete resistance to race E of *O. cumana* (Miladinovic *et al.*, 2012) Line no. 16693 cv. Armavirskii 3497 was completely resistant to different races of *O. cumana*, and the inbred line, AB-VL-8, developed from interspecific hybridization with the rough sunflower (*Helianthus divaricatus*) was fully resistant to races higher than F (Imerovski *et al.*, 2016; Cvejic *et al.*, 2012). Successful identification of quantitative trait loci (QTLs) for *O. cumana* resistance in the sunflower has been reported (Louarn *et al.*, 2016; Akhtouch *et al.*, 2016).

Two cultivars of faba bean (Giza 429 and Giza 674) with good resistance to *O. crenata* have been released in Egypt (Khalil *et al.*, 1993). a new genotype (X-843) derived from Giza 402, was reported to have a good yield and recommended for release in north Egypt (Saber *et al.*, 1999). A high-yielding faba bean cultivar 'Baraca' has been developed in Spain, with a high level of resistance to *O. crenata* (Cubero *et al.*, 1994). However, several faba bean cultivars with resistance to *O. crenata* have been released, all used Giza 402 as the main donor of resistance (Fernández-Aparicio *et al.*, 2012; Rubiales *et al.*, 2016) and resistant varieties against more than two *Orobancha*/Phelipanche spp. were used in the field (Trabelsi *et al.*, 2015, 2016).

High levels of resistance to *O. crenata* were observed in accessions of wild lentil *Lens ervoides*, *Lens odemensis*, and *Lens Orientalis*. Resistance proved to be mainly due to early

hampered tubercle formation (Fernández-Aparicio *et al.*, 2009a).

Chickpea genotypes namely, FLIP 98- 22C, Nayer, and Beja 1, showed partial resistance to *O. foetida* which was due to incompatibility (Nefzi *et al.*, 2016).

Five resistant sesame genotypes with an important trait were identified to have *Ph. aegyptiaca* formed tubercles on their roots but no parasite shoots emerged (Teimouri *et al.*, 2016).

A highly *O. crenata*-resistant pea line, named ROR12, was identified (Bardaro *et al.*, 2016; Pavan *et al.*, 2016). The resistance mechanism may be due to the low release or production of germination stimulants but this does not affect the host yield of the resistant line. Resistance to *O. crenata* has been detected in wild peas (*Lathyrus cicera*) which were found due to a low induction of germination, incompatibility, and escape parasite attack due to precocity or small root biomass (Fernández-Aparicio and Rubiales, 2010). Out of 52 grass, pea accessions screened to *O. crenata* under field conditions, early and very late-maturing accessions were less infected (Fernández-Aparicio *et al.*, 2012). Nine more accessions would have true genetic resistance that was not dependent on the short and long growth length.

Resistance of five oilseed rape (*Brassica napus* L.) cultivars namely; Darmor, Campo, Adrianna, Expert, and Shakira was ascribed to incompatibility or based on a low induction of germination (Gauthier *et al.* 2012).

In tomatoes, some resistance to *Orobanche* was reported from the Russian cultivars "Ora". cv. Gibril-88 and cv. Bolgarskii (Mukumov and Faizieva, 1977).

High to moderately resistance to *O. ramosa* was obtained in the cultivars Tiny Tim, Acora, Cestor, Promodora, Orient, Red Alert and *Lycopersicon pimpinellifolium* LA 1478 with Tiny Tim showed the highest level of resistance (Qasem and Kasrawi, 1995). Kacan and Tursun, (2012) reported several tomato cultivars resistant to *P. aegyptiaca* in Turkey and Tokasi *et al.* (2014) reported other varieties to resist the same parasite under field conditions in Iran. The SL-ORT1 mutant of tomato was shown to be resistant to high concentrations

of *P. aegyptiaca* seeds, and to another three broomrape species: *Ph. ramosa*, *O. cernua*, and *O. crenata* (Dor *et al.*, 2010). The fast-neutron-mutagenized tomato mutant SL-ORT1 was found to be highly resistant to various *Phelipanche* and *Orobanche* spp. SL-ORT1 resistance results from its inability to produce and secrete natural germination stimulants to the rhizosphere (Dor *et al.*, 2011). Tomato cultivar 'Red setter tilling' which is genetically based on a cultivar 'Red setter' is resistant to *Ph. ramosa* because of a reduction in the synthesis of the germination stimulant (Disciglio *et al.*, 2016).

Buschmann *et al.*, (2005) reported on differences in tobacco cultivars to *Orobanche ramosa*. Populations' Dark air-cured tobacco cultivars were the least susceptible to broomrape populations. Tobacco genotypes, two ones, TB 22 and Kramograd NHH 659, did not show any susceptibility to *P. aegyptiaca* in pot experiments (Darvishzadeh, 2016).

### Biological Methods

The following natural enemies could be used against *Orobanche* spp.

#### Insects

Tóth *et al.* (2005) reported 22 species of 10 families on *Orobanche* in Slovakia but only *Phytomyza orobanchia* Kalt. and *Chyliza extenuata*, and two moths, *Diaphora mendica* and *Celypha* spp. caused significant damage. *Chyliza extenuata* as a root feeder and *D. mendica* as a seed capsule feeder is very promising.

*Phytomyza orobanchia* has been successfully applied on a large scale in the former Soviet Union to control *O. cumana* and *O. cernua* (Kapralov, 1974). The insect attacks parasite seed capsules and causes a great reduction in seed production ranging between 29-94% depending on *Orobanche* species. However, the phytophagous insects on *Orobanche* including *Phytomyza orobanchia* (Diptera) occur in most *Orobanche*-infested regions. *Phytomyza* larvae feed on the shoots and especially on the capsules of *Orobanche* spp. (Klein *et al.*,

1999). The insect can damage Orobanche seriously and may reduce seed production by 30% under natural infestation in Syria and by 89% in Egypt.

Other insects reported attacking Orobanche including *Psila* species at the larval stage that attack stem of *O. minor* and *C. extenuate*. *Eulocasta argentisparsa* Hampson, *Smicronyx* spp., *Ophiomyia strigalis* Spencer have been also reported on Orobanche in India and Africa, but are polyphagous (Kroschel *et al.* 1999; Traoré *et al.*, 1999; Klein and Kroschel, 2002).

In general, *P. orobanchia* and *Smicronyx cyaneus* Gyll. (Coleoptera, Curculionidae) are of great importance in biocontrol of Orobanche spp. (Klein and Kroschel, 2002).

### Bacteria

In Petri-dish and pot experiments, Mabrouk *et al.* (2007) found that inoculation of peas with two (*P. SOM* and *P.1236*) of the five strains induced a significant decrease in *O. crenata* seed germination and the number of tubercles on pea roots. An endophytic bacterium, *Pseudomonas* strain PhelS10, originating from tomato roots, suppressed *Ph. aegyptiaca* seed germination and reduced the number of the same parasitic species on tomato roots (Kruh, 2017). Rubialis *et al.* (2018) reported an almost 80% reduction in *P. aegyptiaca* seed germination and a significant reduction in its parasitism was achieved due to the presence of a *Pseudomonas* sp. strain on tomato roots.

Chickpea roots inoculated with *Rhizobium* sp. strain PchAZM reduced the total number of *O. foetida* by up to 90% (Mabrouk *et al.*, 2016). Bouraoui *et al.* (2016) reported that despite the high seed yield reduction of faba bean caused by *O. foetida*, the inoculated crop with Mat strain of rhizobia showed an average yield three-fold higher than the control. Two *Rhizobium leguminosarum* strains (Mateur and Bouselem) were selected as potential inoculants to protect faba beans against *O. foetida* and to promote the host's growth in pot and rhizotron experiments (Bouraoui *et al.*, 2012). Inoculation of chickpeas with *Rhizobium* strains significantly decreased *O. crenata* and *O. foetida* seed

germination and several tubercles (Hemissi *et al.*, 2013; Mabrouk and Belhadj, 2014).

### Fungi

Sixty-two fungi species were isolated from different Orobanche species (Thomas *et al.*, 1999a), eight of these showed pathogenicity to Orobanche, and four belonging to the genus *Fusarium*, among which *F. oxysporum* f. sp. *Orthocera* (1999a) and *Fusarium arthrosporioides* (Amsellem *et al.*, 2000) are thought to be developed as mycoherbicides. Babalola (2010) reported that *F. arthrosporioides* killed 56% of *O. aegyptiaca* tubercles infesting tomatoes while its mycelia had no damage effects on tomato roots. Other reports mentioned 16 fungi species attack different Orobanche species including *O. aegyptiaca*, *O. cernua*, *O. crenata*, and *O. ramosa* but only *Ulocladium*, *Fusarium* (*F. oxysporum* var. *orthoceras*; *F. orobanchas*), *Alternaria*, and *Rhizoctonia solani* proved highly effective and selective against *O. ramosa* in tomato and reduced infestation by 80%, *Ulocladium atrum* as effective as a biocontrol agent for *O. crenata* at high humidity.

*Fusarium arthrosporioides* E4a and *F. oxysporum* E1d, as well as strains of bacteria, were isolated from diseased, juvenile, Orobanche flower stalks. They are pathogenic to *O. aegyptiaca*, *O. crenata*, and *O. ramosa*. Tóth *et al.* (2005) reported different pathogens observed on *O. alba* and *O. flava*.

In Russia, good results were obtained adding *F. oxysporum* into the planting holes of watermelon (Product F). However, investigations concentrate on *F. oxysporum* f. sp. *orthoceras*, reported control *O. cumana* in sunflower by 90%, and *O. ramosa* and *O. aegyptiaca* were also susceptible (Bedi, 1994). The same fungus decreased Orobanche infestation to tobacco by 75.23% and increased crop yield by 80.5% (Mazaheri *et al.*, 1991). It was also reported to control *O. cumana* by 74-90% in naturally infested fields (Bedi, 1992) and recommended for *O. cumana* control in sunflower (Bedi and Donchev, 1995; Bedi and Sauerborn, 1999).

The microconidia or air-dried chlamydospore were formulated as granules with wheat flour and kolin (Pesta) as a rich biomass of *F. oxysporum* Schlecht f. sp. *orthoceras* (Appel and Wollenw.) and found effective against *O. cumana* in sunflower (Müller-Stöver *et al.*, 2002) and reduced parasite shoot emergence by 64% (Müller-Stöver *et al.*, 2004). The combination of *F. oxysporum* Schlecht. f. sp. *orthoceras* with BTH Benzo (1,2,3) thiadiazole-7-carbothioic acid S-methyl ester, a product that induced resistance to *O. cumana* in sunflower was highly effective (Müller-Stöver *et al.*, 2005).

Application of the fungus granules into potted soil reduced the number and dry weight of *Orobanchae* shoots by more than 90%. *Orobanchae* shoots treated with the conidial suspension of the fungus dead by 75% in two weeks (Müller-Stöver *et al.*, 2009).

Conidial suspension of two selected isolates of *F. oxysporum* significantly reduced germination, attachments, and tubercles of *O. crenata*. The microconidia and chlamydospores of both isolates formulated as mycoherbicides greatly reduced the number of emerged *Orobanchae* shoots, their heights, attachments, and dry weights. Meanwhile, disease incidence and disease severity of emerged shoots were enhanced (Nemat Alla *et al.*, 2008). *Fusarium oxysporum* caused heavy reactive oxygen species (ROS) damage in *Orobanchae* induced significant irrevocable genotoxic effects on the DNA of *Orobanchae*, degraded protein metabolism and synthesis, and finally triggered apoptosis (Aybeke, 2017a). It caused heavy hormonal disorder, triggered only SA-mediated defense, and induced intensively the accumulation of phenolic substances in *Orobanchae*. *Fusarium oxysporum* causes lethal physiological damage on *Orobanchae* spp. (Aybeke, 2017b).

*Fusarium solani* was reported to suppress the growth of *O. ramosa* in tomatoes (Gold *et al.*, 1979). Other plant pathogens reported including, *Alternaria*, *Fusarium*, and *Trichoderma* were also found infesting *O. crenata* in Egypt (Abdel-Kader *et al.*, 1998). *Ulocladium atrum* infected and destroyed underground tubercles and emerged shoots (Linke

*et al.*, 1992). *Ulocladium botrytis* Preuss has been also found pathogenic to *O. crenata* (Linke *et al.*, 1992; Müller-Stöver and Kroschel, 2005). *Myrothecium verrucaria* (Alb. and Schwein.) Ditmar isolated from faba bean roots has been found to inhibit germination of *O. crenata* seeds and the conditioned seeds exposed to GR24 due to the production of the macrocyclic trichothecene verrucaric acid (El-Kassas *et al.*, 2005). The infection of *V. faba* by *O. crenata* could be prevented by the addition of the fungus spores to infested soil by the parasite.

Application of mycoherbicides *Trichoderma harzianum* and *Trichoderma viride* followed by foliar spray with glyphosate was the most appropriate treatment, resulting in the highest reduction in *O. ramosa*. Soil treatment with *T. harzianum* and *T. viride* alone or plus an aerial spray of glyphosate (50 ppm) reduced *O. crenata* and *O. ramosa* infection and increased peas, faba bean, and tomato yields (Abdel-Kader and El-Mougy, 2009). *Trichoderma harzianum*, *T. harzianum* + *Rhizobium leguminosarum* and *R. leguminosarum* reduced *O. crenata* incidence in faba bean by 11.5%, 8.4% and 7.6%, respectively. *Trichoderma harzianum* + *R. leguminosarum* treated plots had the highest grain yield (Aregawi, 2017).

Arbuscular mycorrhizal (AM) fungi root exudates hurt the germination of *O. cumana* induced by germination stimulants (Louarn *et al.*, 2012; 2016) and a similar effect could be obtained with AM spore exudates. Production and exudation of strigolactone were significantly reduced by AM fungi symbiosis in tomatoes and the germination inducing activities of *P. ramosa* were significantly ( $p < 0.01$ ) lower in tomato plants colonized by AM fungi than in free tomato plants (Lopez-Raez *et al.*, 2011). Mycorrhizal root exudates had negative effects on *O. cumana* germination (Louarn *et al.*, 2012). Root exudates from pea plants colonized by AM fungi showed low germination inducing activities to *O. crenata*, *O. foetida*, *O. minor*, and *P. aegyptiaca* (Fernández-Aparicio *et al.*, 2010b).

The multiple-pathogen strategy was recently developed at which two or more pathogens are used jointly and applied

before or after parasite emergence. Some of these fungi mixtures resulted in a significant reduction in the several emerged *O. cumana* shoots (Charudattan, 2001). Amsellem *et al.* (2001) and Cohen *et al.* (2002) reported a reduction in *O. aegyptiaca* attachment to tomato plants in glasshouse experiments using host-specific strains of *F. oxysporum* and *F. arthrosporioides*. The combination of Benzothiadiazole herbicide and *F. oxysporum* f. sp. *orthoceras* successfully controlled *O. cumana* and reduced parasite emergence up to 100% (Müller-Stöver *et al.*, 2005).

Encapsulation of fungal propagules in a solid matrix has been already developed (Amsellem *et al.*, 1999; Quimby *et al.*, 1999). Pesta granules showed high efficacy in controlling *O. cumana* in the glasshouse (Kroschel *et al.*, 2000; Müller-Stöver, 2001; Elzein, 2003).

Another approach is the engineering of hypervirulence genes into weed-specific pathogens which encode enzymes degrade parasite phytoalexins and enhance the production of fungal toxins (Gressel, 2002; Gressel *et al.*, 2004).

## Chemical Methods

### Fumigants

Methyl bromide had been used against *Orobanche* in cash crops but in a limited area, under tunnels, plastic, and glasshouses for the high-cost justification. Volatile compounds such as methyl bromide, ethylene dibromide for *O. crenata* control in pea (*Pisum sativum* L.), metham-sodium for *O. aegyptiaca* in tomato (Jacobsohn *et al.*, 1987), or formalin were found effective against broomrapes (Foy *et al.*, 1989). The practice of soil fumigation has caused environmental problems (Shabana *et al.*, 2003) and therefore, it was banned including Methyl bromide in different countries.

### Herbicides

Below are herbicide treatments recommended for parasite control in different crops.

### Seed Treatment

Seed treatments with imidazolinones proved effective for controlling *O. crenata* in faba bean. Promising results on

Imazethapyr effectiveness against *O. crenata* through faba bean and pea seed treatments have been reported (Jurado-Exposito *et al.*, 1996; 1997).

Coating sunflower seeds with pronamide lowered *Orobanche* shoot dry weight and increased sunflower yield (Sanchez *et al.*, 2003). Soaking sunflower seeds in 0.1% boric acid or copper sulfate solutions increased plants' resistance to herbicides and *Orobanche* sp. (Aziz, 1989). Seed treatment with 40 ppm benzothiadiazole, Bion for 36 hours completely prevented infection of *O. cumana* (Buschmann *et al.*, 2001).

Tomato seeds immersed with chlorsulfuron (0.05-0.1% solution) or triasulfuron (0.15-0.30% solution) for 5-10 minutes caused severe phytotoxicity on emerging crops. In contrast, seed coating with lower doses (0.05-0.1 mg/kg) of chlorsulfuron, triasulfuron or sulfosulfuron was safe for the crop. Mustard seed treatment with triasulfuron, sulfosulfuron, and chlorsulfuron delayed *Orobanche* attachment and emergence but the effect was inconsistent at longer periods. High doses of the herbicide seed treatment resulted in poor crop seed germination and growth suppression (Punia *et al.*, 2012).

Soaking broad beans and lentils seeds for 5 minutes in 0.01% imazethapyr solution or coating at 20-40 g/ha (at a sowing rate of 160 kg/ha) did not affect seed germination and crop growth but resulted in 60-80% *O. crenata* control. Imazethapyr followed by late post-emergence application of imazapyr (5g/ha) caused more than 95% weed control. Imazethapyr or with imazapyr at 5 g/ha to *P. sativum* seeds controlled *O. crenata* and seeds treated at late post-emergence resulted in excellent *Orobanche* control (Jurado-Exposito *et al.*, 1996).

Effective seed treatments were found with imazapyr for broad bean and imazethapyr in lentils (Jurado-Exposito *et al.*, 1997). However, sulfonylurea, imazethapyr, and imidazolinone were found effective in many host crops.

### Soil and Foliar Applied Herbicides

Soil-incorporated herbicides of dinitroanilines, sulfonylureas, substituted ureas showing host crop

selectivity and significant soil residuality for better control of *Orobanche* (Parker and Riches, 1993). Sulfonylureas prevented broomrape emergence from growing on broad-leaved weeds in a non-host cereal crop. Application of metsulfuron-methyl (3 g/ha), chlorsulfuron (15 g/ha) or triasulfuron (22.5 g/ha) gave 100% control of *O. ramosa* with no damage to wheat or barley crops (Matthews, 2002).

Rimsulfuron selectively controlled *O. aegyptiaca* in tomatoes when applied through drip irrigation but the repeated application may be necessary for long-term weed control (Kleifeld *et al.*, 1994). Three foliar applications of rimsulfuron (12.5 g/ha) followed by irrigation, at two weeks intervals after crop emergence controlled *O. aegyptiaca* in potato (Goldwasser *et al.*, 2001) but gave different results in tomato because of differences in the irrigation system. The same herbicide at 10 to 20 g a.i./ha, reduced broomrape dry weight and number of shoots and was selective on tomatoes (Vouzounis and Americanos, 1998) but was toxic to eggplant. These authors reported glyphosate and sulfosate applied twice at 30 to 50 g a.i./ha were effective against *O. ramosa* but reduced tomato yield.

Below is the effect of chemical control of *Orobanche* spp. in different crops

#### **Broadbean (*Vicia faba*)**

Trifluralin applied pre-sowing and linuron post sowing gave the highest seed yield of broad bean (*Vicia faba*) infected with *O. crenata* (Zahran, 1982).

The effectiveness of glyphosate acid at 60-120g a.i./ha in controlling *O. crenata* in broad bean has been well documented (Nassib *et al.*, 1984; Mesa-Garcia and Garcia-Torres, 1985; Salem *et al.*, 1989). Ibrahim *et al.*, (2000) reported that glyphosate resulted in high a significant reduction in *Orobanche* spikes ranging from 92 to 100%. This high efficiency against *Orobanche* increased seed yield by 3,296 and 2,550 t/ha in two locations, respectively over means of all sites (Dongola *et al.*, 2000).

Hamid *et al.*, (2000) reported that application of butralin (2.85 Kg a.i./ha) followed by glyphosate (58 g a.i./ha),

imidazolinone (214.2 g a.i./ha), and hand hoeing (twice) reduced the fresh weight of *Orobanche* spikes by 95, 79, and 84%, respectively.

Imazethapyr, imazapyr, and chlorsulfuron were the most effective for *O. crenata* control in legumes (Garcia-Torres and Lopez-Granados, 1991), and imazethapyr against *O. aegyptiaca* and *O. foetida* (Geipert, 1997). Garcia Torres *et al.* (1998) reported selective *O. crenata* control in faba bean by pre-emergence and post-emergence applications of imazethapyr, imazapyr, and imazaquin.

#### **Lentils (*Lens esculentus*)**

Glyphosate at 40 or 60 g/ha controlled *Orobanche* and increased lentil yield by 117 and 51%, respectively (Arjona-Berral and Garcia-Torres, 1983).

#### **Peas (*Pisum sativum*)**

*Orobanche crenata* cause 100% yield loss at high infestation. Two or three applications of glyphosate at 150g/ha gave the highest yield under light infestation (Jacobsohn and Kelman, 1980). Post-emergence of imazethapyr at 20 g/ha on *Pisum sativum* and *Pisum arvense* a month after planting and at 20-40 g/ha two weeks later, was effective against *Orobanche* and selective to pea plants (Jacobsohn *et al.*, 1998). Ethylene dibromide alone or with chloropicrin controlled *O. crenata* and *O. cernua* (Jacobsohn *et al.*, 1982). A pre-emergence tank mixture of propyzamide and methabenzthiazuron was effective against *O. crenata* (Schlingloff and Alkamper, 1992).

#### **Potato (*Solanum tuberosum*)**

Single and sequential applications of rimsulfuron between 20 and 50 g a.i./ha significantly reduced *O. ramosa* shoot number and dry weight. Three applications were most effective (Haidar *et al.*, 2005b). Best results on *Orobanche* control and potato selectivity were obtained with rimsulfuron (12.5 g a.i./ha) followed by sequential 3 foliar application of glyphosate at 100 g a.i./ha (Haidar *et al.*, 2005b). *Orobanche aegyptiaca* and *O. ramosa* were

controlled in potato-infested soils by split foliar applications of low rates of imazapic and rimsulfuron. Three applications of imazapic at 4.5 g/ha each, after crop emergence and re-applied at 2-week intervals, prevented Orobanche infestation (Goldwasser *et al.*, 2001).

#### **Vitch (*Vicia* spp.)**

Nadal *et al.* (2008) reported that glyphosate at 35–67 g a.i./ha, applied when *O. crenata* attachment was at the tubercle stage of development increased seed yield of narbon bean (*Vicia narbonensis*).

#### **Cabbage (*Brassica oleracea* var. *capitata*)**

Orobanche aegyptiaca was effectively controlled with glyphosate at 60-100 g a.i./ha or imazaquin at 5-10 g a.i./ha. Trifluralin at 0.9 Kg a.i./ha may have a beneficial effect in reducing Orobanche infestation (Americanos and Vouzounis, 1995).

#### **Mustard (*Brassica juncea*)**

Glyphosate (25 g/ha) applied twice at 30 days after sowing followed by 50 g/ha at 55 days provided 65-85% control of Orobanche up to harvest without any crop injury and improved yield from 12 to 41% over the traditional farmers' practice in different years of the study (Punia *et al.* 2010; Sheoran *et al.*, 2014).

#### **Carrots (*Daucus carota*)**

Glyphosate (1-1.5 Kg/ha) resulted in moderate control of Orobanche sp. and was recommended for *O. crenata* and *O. aegyptiaca* control (Jacobsohn and Kelman, 1980).

#### **Celery (*Apium graveolens*)**

Infestation of *O. ramosa* and *O. aegyptiaca* was reduced by glyphosate (20-50g/ha). The herbicide was most effective at a high rate (Americanos, 1991).

#### **Parsley (*Petroselinum sativum*)**

Orobanche crenata and *O. aegyptiaca* were completely controlled with split foliar application of imazapic (2.5–5 gha-1) or glyphosate (36–72 gha-1); applied on 5–7 leaf

parsley before the first cutting and on the young new growth after each cutting (Goldwasser *et al.*, 2003).

#### **Oilseed rape (*Brassica napus* L.)**

Foliar and soil applications of Acibenzolar-S-methyl reduced *O. ramosa* attachment by 70% and prevented crop biomass loss (Veronesi *et al.*, 2009).

#### **Sunflower (*Helianthus annuus*)**

Propyzamide applied to sunflower plants in the glasshouse followed by sprinkler irrigation reduced or delayed *O. crenata* and *O. aegyptiaca* infestation. Application of the herbicide with irrigation water was most effective. Direct application of glyphosate and propyzamide to the soil through an irrigation system was effective in controlling *O. cernua* (Kleifeld and Herzlinger, 1984).

Pre-sowing soil incorporation of propyzamide plus thiram kept sunflower free of Orobanche until the end of flowering (Herzlinger and Kleifeld, 1985). Pre-emergence application of oxyfluorfen at 1 and 2 l/ha reduced *O. cumana* density and further reduction was obtained with pre-sowing treatment of trifluralin at 3.5 l/ha and pre-emergence of oxyfluorfen at 1 l/ha. Oxyfluorfen inhibited the formation of secondary haustorium of *O. cumana* (Horvath and Osztrogonac, 1991).

Imazethapyr, imazapyr, and chlorsulfuron were most effective against *O. cernua* and recommended for parasite control (Garcia-Torres and Lopez-Granados, 1991). Imazapyr at 10-15g/ha was effective in controlling *O. cernua* (Garcia-Torres *et al.*, 1995) and pre-emergence treatment of imazethapyr was also effective (Garcia-Torres *et al.*, 1998). In a post-emergence treatment, imazethapyr at 26.6-53.2 g/ha killed Orobanche nodules (Alonso *et al.*, 1998).

Imazapic reduced *O. cumana* infestation in post-emergence and in sequential treatments in sunflower in irrigated and non irrigated fields and sunflower was not affected (Aly *et al.*, 2001).

### **Tobacco (*Nicotiana tabacum*)**

Foliage application of maleic hydrazide triethanolamine salt at 6 and 9 kg/ha completely killed *Orobanche* spp. and increased leaf yield and quality (Darbinyan *et al.*, 1977). It reduced *Orobanche* spikes at 0.25 - 0.75 kg a.i./ha applied at 30 or 40 days after transplanting and up to the flowering stage (Dhanapal, 1996). Two applications at 1-8 l/ha resulted in 90% control of *O. ramosa* (Danko, 1993a) while Imazapyr and EPTC were less effective. Imazaquin at 0.07+0.1 kg, maleic hydrazide at 0.45+0.45 kg, and sulfosate at 0.2+0.3 kg all reduced number of *O. ramosa* plants/pot (Lolas, 1994).

Glyphosate and glyphosate trimesium (touchdown) at 100-150 ml/ha were also used to control *O. ramosa* in tobacco (Musselman, 1993). At 0.035% applied to the lower parts of tobacco plants in spot treatment it was effective against *O. ramosa* (Danko, 1993b), and under field conditions, glyphosate in 2, 3, or 4 treatments with a total dose of 1000ml/ha gave good control of *O. ramosa* (Sandri *et al.*, 1998). At 0.5 kg a.i./ha applied at 60 days after transplanting and imazaquin at 0.01 kg a.i./ha at 30 days after transplanting reduced *Orobanche* population by almost 80% and increased tobacco leaf dry weight by more than 40% (Dhanapal *et al.*, 1998).

Tobacco gave a similar yield to weed-free treatment when 1.5 kg fluchloralin, 0.75 kg bentiocarb, or 0.1 kg oxyfluorfen, and 4-inter-row cultivation were done (Metha *et al.*, 1985). Pre-plant application of fluchloralin at 2 kg/ha gave a high tobacco yield equal to the weed-free treatment. Fluchloralin and 4 kg diphenamid/ha were highly selective to tobacco while pepulate and fluchloralin each at 3 kg/ha were highly effective against *O. cernua* (Palled *et al.*, 1985).

Allyl alcohol at 0.1-0.2 concentration sprayed 4 times at weekly intervals reduced *Orobanche* infestation (India, Central Tobacco Research Insitute, 1979). Chlorsulfuron (2g/ha), imazaquin (70 and 100g/ha), and imazapyr (20-30 g/ha) were applied pre-transplanting, and glyphosate (200-300g/ha), glyphosate-trimesium (300 and 400 g/ha), imazaquin (70 and 100 g/ha) and maleic hydrazide (450 g/ha) applied over tobacco plants were effective in

controlling *Orobanche* with no phytotoxicity in oriental cultivar (Lolas, 1997).

### **Tomato (*Lycopersicon esculentum*)**

Glyphosate and sulfosate applied twice at 30 to 50 g a.i./ha were effective against *O. ramosa* and *O. aegyptiaca* on tomato and eggplant but reduced tomato yield. Variations between tomato cultivars were detected for glyphosate treatment at 150 ppm. glyphosate in 250l water /ha applied at 2-true leaf stage (Foy *et al.*, 1988).

Three applications (at bud formation, near flowering, and beginning of ovary formation) of glyphosate at 150 g/ha resulted in the highest tomato yield and lowest *O. ramosa* number (V"lchev *et al.*, 1995). Metham-sodium in drip-chemigation controlled *O. aegyptiaca* at 20-100 l/ha (Kleifeld *et al.*, 1991). Polyethylene mulching of the metham treated soil drastically improved metham performance and *O. aegyptiaca* control.

In pot experiments, chlorsulfuron applied at 37 and 180 g a.i./ha was the most effective for *O. ramosa* control and least toxic to tomato (Syka and Eleftherohorinos, 1991). *Orobanche aegyptiaca* control in tomato was achieved with the 3-split application of chlorsulfuron at 2.5 g a.i./ha and triasulfuron at 7.5 g a.i./ha (Hershenhorn *et al.*, 1998). Qasem (1998) reported excellent control of *O. ramosa* using chlorsulfuron at 2.44 g a.i./ha in irrigation water or directly incorporated into the soil.

Bensulfuron, chlorsulfuron, nicosulfuron, primsulfuron, trimsulfuron, thifensulfuron, and triasulfuron were tested for their effects on seed germination of *O. aegyptiaca* at preconditioning and germination stages. All herbicides reduced radical elongation of the parasite. Chlorsulfuron and triasulfuron applied at 2.5 and 25 µM a.i. and rimsulfuron at 5µM a.i. at preconditioning and germination in vitro almost completely inhibited parasite development (Hershenhorn *et al.*, 1998). Single application of rimsulfuron (25 g a.i./ha) to tomato at 10 days after planting and split applications at 10 and 20 and 10, 20 and 30 days after planting significantly reduced number of *O. aegyptiaca* inflorescences.



Chlorsulfuron and triasulfuron applied directly to soil at rates  $\geq 3.75$  g a.i./ha completely controlled *O. aegyptiaca*. Rimsulfuron at 10 to 20 g a.i./ha reduced Orobanche weight and number of shoots (Vouzounis and Amerikanos, 1998). Primisulfuron and chlorimuron each at 22.5 g a.i./ha reduced the number of parasite inflorescence (Hershenhorn *et al.*, 1998).

Three split applications of 2.5 g/ha chlorsulfuron through sprinkler irrigation, starting two weeks after transplanting and at 10-14 days intervals followed each application by 300 m<sup>3</sup>/ha irrigation, controlled 80-90% of Orobanche with no phytotoxic effect on tomato (Hershenhorn *et al.*, 1998). Chlorsulfuron, effectively controlled Orobanche's late emergence around drip emitters in tomatoes (Kleifeld *et al.*, 1999), but results were inconsistent in other tests. Chlorsulfuron at 2.38g, 7.14g, and 11.9 g/ha gave 63.45%, 100%, and 81.81% parasite control, respectively (Dongola *et al.*, 2000).

Sulfosulfuron was highly effective and selective for *O. aegyptiaca* control (Eizenberg *et al.*, 2001) but chlorsulfuron and triasulfuron were most effective through chemigation. The herbicide acts mainly through the soil. Successful chemical control of *O. aegyptiaca* in processing tomato was achieved with sulfosulfuron and imazapic (Parker, 2009). Two (14 and 42 days after planting) or three (14, 28, 42 days after planting) foliar applications of 50 g ha<sup>-1</sup> monitor effectively controlled *O. aegyptiaca* in tomatoes. These Effective control of Orobanche in tomatoes grown under irrigation was achieved by pre-emergence application of sulfosulfuron at 75 g/ha (Dinesha *et al.*, 2012).

Deep incorporation of dazomet at 3 weeks before transplanting tomato prevented or delayed Orobanche emergence. Dazomet, which releases the toxic gas methyl isothiocyanate to control *Phelipanthus mutellii*, was confirmed under field conditions in Australia (Prider and Williams, 2014).

Imazethapyr 20, 40 and 80 g/ha resulted in 77.72%, 72.7 % and 78% control, respectively. Oxadiazon controlled Orobanche spp. when applied in sprinkler irrigation to the

root zone of tomato (Kleifeld *et al.*, 1982). Imazaquin and glyphosate applied at 37 and 180 g a.i./ha, respectively, controlled Orobanche but imazaquin reduced crop yield (Syka and Eleftherohorinos, 1991).

Trials for chemical control of *O. ramosa* in tomatoes showed that imazethapyr and chlorsulfuron were effective for both crop/ parasite situations (Dongola *et al.*, 2000). Application of the imidazolinone systemic herbicide Cadre (Imazapic ammonium salt) on tomato foliage prevents fruit setting by damaging the reproductive system. Tomato flowers throughout the growing season, with fruit set peaking at 50 to 60 days after planting. However, early treatments with monitor followed by Cadre application after the fruit setting peak completely controlled *O. aegyptiaca* in tomatoes without causing any damage to the yield (Lande *et al.*, 2005). Application of imazapic and imazapyr during tomato cultivation using an IR tomato mutant demonstrated high *P. aegyptiaca* control efficacy (Dor *et al.*, 2016). A foliar application of maleic hydrazide to tomato reduced *P. aegyptiaca* attachment on the host roots without any influence on tomato foliage or root dry weight (Samejima and Sugimoto, 2018).

### Advanced Biotechnology

These include the use of nanotechnology (P'erez-de-Luque and Rubiales, 2009), genetic engineering that enables the use of herbicides including the non-selective chemical on crop plants and targeted weed species providing that the herbicide-resistant gene is transferred into crop plants (Qasem, 2013). Transgenic allelopathic crops that could prevent parasite seed germination, reduce or delay the release of parasite seed germination stimulant, or prevent attachment of the parasite or haustorial development and Gene Silencing technology effectively through a segment of a double-stranded RNA (dsRNA) inserted in host plants and can move into the parasite and inhibit parasite target gene leading to its impaired expression (Fire *et al.*, 1998; Dubey *et al.* 2017), preventing its function and reducing parasitism.

### Integrated Control Methods

Not all satisfactory measures of control have been found so far, therefore a combination of suitable measures for a specific situation in the sense of an integrated approach seems to be the most appropriate way to deal with the problem. The results obtained from any single control method were insufficient. Combining two or more methods is necessary to easier deal with the problem. In this regard analysis of the farming system looks important ([http://www.uni-hohenheim.de/~www380/parasite/oro\\_path.htm](http://www.uni-hohenheim.de/~www380/parasite/oro_path.htm)).

The only effective way to counteract parasitic weeds problems is to apply an integrated approach (Rubiales and Fernández-Aparicio, 2012) through a combination of all possible weed control methods and tools. These include preventive, cultural; mechanical; Physical; biological; and future research and biotechnologies and chemical methods

It is to conclude, that until now developments in control strategies are not advancing beyond agronomic practices,

resistant varieties, and possible chemical control by herbicides. Therefore, integrated methods through varying agronomic measures are always recommended for some acceptable level of parasite control and to avoid total yield loss under heavy infestation. Taking into consideration the cost, persistence, low selectivity and negative environmental impacts of some recently reported effective sulfonylurea and imidazolinones herbicides against certain parasite species, alternatives, and eco-friendly methods are necessary. These may be recently thought through the use of safe natural products, plant materials, and their byproducts, allelopathy, resistant varieties, trap and catch species in rotation with host crops, botanical herbicides, growth promoters, and fertilizers, mechanical and physical methods including plastic mulch and soil solarization and even eating broomrape might be all considered as part of the integrated control package. All are strongly recommended for parasites and other weeds control in general.

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## أنواع الهالوك ( Orobanchae spp.) التحدي والإدارة: مراجعة

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تاريخ استلام البحث: 2021/7/1 وتاريخ قبوله: 2021/8/29.

### الملخص

تعد أنواع الهالوك (الأوربانشي) من الأعشاب الطفيلية الأكثر تدميراً وضرراً للزراعة، وتتوضع هذه الطفيليات على جذور العديد من الأنواع النباتية المزروعة والبرية التي تنضوي تحت عائلات نباتية عديدة، وتختلف هذه الأنواع الطفيلية في الشكل الظاهري والعوائل النباتية التي تهاجمها على الرغم من أنها تشترك في عدد كبير من أنواع العوائل المختلفة، وتظهر أنواع معينة من الهالوك أكثر تخصصاً من غيرها في تطفلها على عوائل ذات طبيعة نمو معينة كالأشجار المثمرة والحرثية، وكل أنواع الهالوك هي أنواع إجبارية التطفل تغتفر إلى صبغة اليخضور (الكوروفيل) وهي تعد بذلك غيرية التغذية تعتمد بشكل كامل على عوائلها النباتية في الحصول على الغذاء و/أو الماء حيث تحصل عليها من خلال أعضاء امتصاص خاصة تسمى ممصات (Haustoria) تقدم هذه المراجعة العلمية استعراضاً للمعلومات التي تتعلق بحياة وبيئة وانتشار وعلاقة التطفل بين العائل والطفيل. والأهمية الاقتصادية، وطرق الإدارة للأنواع واسعة الانتشار والأكثر أهمية من الهالوك في الأردن والعالم التي تسبب خسائر فادحة في إنتاج الكثير من المحاصيل الاقتصادية المهمة، والقضاء على الإنتاج بشكل كامل في الإصابات الكثيفة، تم تضمين ومناقشة أحدث ما وصل إليه الباحثون من طرق مكافحة المتبعة حالياً في الأردن وفي مناطق مختلفة من العالم.

**الكلمات الدالة:** الأعشاب الطفيلية، أنواع الهالوك (الأوربانشي)، العوائل النباتية، الإدارات.