Management of *orobanche* in field crops- *A review*

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Abstract

Broomrapes (*Orobanche* sp.) are a root holoparasitic plant devoid of chlorophyll and entirely depending on the host for nutritional requirements. They cause considerable yield losses (5-100 %) in the crops, especially in the drier and warmer areas of Europe, Africa and Asia where it is reported to mainly parasitize species of leguminous, oilseeds, solanaceous, cruciferous and medicinal plants. It is a serious root parasite threatening the livelihood of the farmers with its devastating effect on the some of aforementioned crops. The long-term impact of the broomrapes is even more serious: their seeds may easily spread to other fields, and can persist in soil up to 20 years, leading to an accelerated increase in the infested areas in which susceptible crops are under danger. *Orobanche* seed dispersal is facilitated by man, agricultural tools, crop seeds, propagules and also by animals through their excreta.

This review will discuss and summarize alternative methods viz preventive, physical, chemical, agronomic, biological, crop resistance and integrated methods which are needed to manage this parasite. However, the main concern is that, up to date, no single cheap method of control proved to be effective, economical and complete in protection against this parasite. For that reason, an integrated approach is needed in which a variety of such techniques are combined, in order to maintain parasite populations below threshold levels of damage.

Keywords: *Orobanche*, broomrape, preventive, physical, chemical, agronomic, biological, crop resistance and integrated control methods

1. Introduction

Broomrapes are holoparasites and only germinate in response to specific chemicals released by the host plant. Following germination, the seedlings attach to the host roots by the production of specialized feeding structures, described as haustoria that form a functional bridge into their hosts. Broomrapes spend most of their life cycle underground, where they undergo processes of germination, haustorial differentiation from the radicle, haustorial penetration of the host, formation of

vascular connection with the host, acquisition of host nutrients, and storage of resources in a parasite organ called the tubercle or nodule (Fernández-Aparicio *et al.*,2011). Haustoria penetrate the host tissues until they reach the vascular system for uptake of water, nutrients, assimilates, and grow at the expense of the host plant's resources (Joel *et al.*, 2007). Because the infection and pathogenesis processes take place underground, damage to the crop occurs prior to the

emergence of the parasite and diagnosis of infection. The particular characteristics (underground development, attachment to the host roots) of this pathogenic weed hamper the development of effective control strategies. In addition, a single broomrape plant can release more than 500,000 seeds, which are known to remain viable for decades in the soil. This provides the parasite with a great genetic adaptability to environmental changes, including host resistance, agronomical practices and herbicide treatments (Joel *et al.*, 2007).

Due to this, the available methods of control against broomrapes have not proven as effective, economical and applicable as predicted (Perez-de-Luque *et al.*, 2010, Goldwasser *et al.* 2008. Although several potential control measures were developed over the past few decades for some crops, any approach applied alone is often only partially effective and the results are sometimes inconsistent due to variable environmental conditions. Therefore, the only effective way to combat weedy root parasite like *Orobanche* to date is through an integrated approach, combining a variety of measures in a concerted manner.

Two broomrape species (*O.crenata* and *O.ramosa*) attack mainly the crops of apiaceae family such as *Daucus carota, Apium graveolens, Petroselinum sativum, Foeniculum vulgare,* and *Fabaceae family: Vicia faba, Pisum sativum, Lens culinaris, Cicer arietinum, Medicago sativa.* In most cases *O.cernua* and *O.ramosa* attack the crops of Solanaceae family like *Lycopersicon esculentum, Nicotiana tabacum, Solanum tuberosum, Solanum melongena* and cause the yield loss of more than 75 percent (Kamel F.2005).

2. Preventive measures

The strength of broomrape lies in its ability to form a bank of seeds in the soil. A management or eradication program must aim at reducing this seed bank, while minimising the production of new seeds and their dispersal to new sites. Quarantine is therefore an

essential element in control or eradication programs. The best option for winning against broomrapes is avoiding the fight. It is not possible when the fields are already infested with the seeds, but preventive measures must be taken into consideration to avoid spreading the infestation into neighbouring fields.

The main ways for broomrape seeds dispersal are through machinery and tools, and together with the host seeds; proper phytosanitary measures in and around the field are necessary to reduce the spread of *Orobanche*. Farm equipment and machinery should be cleaned prior to their use in uninfested fields. Special care must be applied to disinfestation and cleaning of field machinery and harvesters, and avoid trucks going from infested to non-infested fields. Containment is a must to avoid spreading of the infestation and eradication programs should be considered. *Orobanche* shoots should be removed prior to flower opening. The collected shoots should be burnt or disposed off properly. Good extension agents could easily convince the farmers to execute such task, especially when they made aware of the tremendous production of *Orobanche* seeds per plant. One important spreading agent of various weeds, including *Orobanche,* is the uncontrolled movement of grazing animals. Grazing animals should be forbidden to enter un-infested fields after grazing infested areas (Panetta and Roger, 2005). Furthermore, farmers should use certified seed in order to insure themselves it is clean of parasite seeds.

The results indicate that the ITS-based markers can also provide a reliable diagnostic tool to detect three damaging broomrape species (*P. aegyptiaca, O. Cumana* and *P. crenata*) in a soil sample. ITS-350 primers successfully amplified a (350 bp) PCR product. When soil samples were inoculated with *P.aegyptiaca, O. cumana* or *P. crenata* seeds or tissue. As expected, the UCP-555 primers amplified a PCR product (555 bp) of the same samples (Radi A.*et al*., 2012).

Fresh contaminated manure aggravates *Orobanche* problem. Farmers should be instructed to use fermented manure, as fermentation process kills the seeds of the

parasite. Pre-plant composting fresh manure under plastic mulch in the planting rows causes *Orobanche* seeds to lose viability within six weeks, and reduces *Orobanche ramosa* infestation on many vegetables. This practice could be a useful asset in high value crops. Fermenting manure in the farm can be easily practiced by subsistent farmer without much input and can aid sustainable farming strategy (FAO, 2008).

Strict quarantine measures, at various levels, national and international, help in preventing the introduction of the parasite into parasite-free areas. Technical inspection of imported agricultural materials should be carried out by a subject matter specialist in parasitic weeds (FAO, 2008).

3. Physical methods

Soil solarisation is the heating of soil by sunlight trapped under a mulch of black, or more usually clear, polyethylene film. The temperatures of 48-57 ºC kill Orobanche seeds that are in the imbibed state; therefore soil must be wet at the time of treatment. Seeds of *O. ramosa* can survive 35 days at 50 ºC in dry air, but are quickly killed by temperatures of 40 ºC when wet. The temperature increase achieved is primarily in the result of the elimination of evaporation, but is also partially because of the greenhouse effect created. This technique has been used successfully on cropping land in many countries around the world like Middle East with an endemic *Orobanche* problem, as a pre-planting treatment for tomato, carrot, eggplant, faba beans and lentils. Soil solarization has been proven to be the most effective methods in controlling broomrape in open crops fields (Haidar and Sidahmad, 2000).This approach has attracted the interest in many warm-climate countries because of its effectiveness, simplicity, and safety for humans, plants, and the environment. Solarisation entails covering wet soil with transparent polyethylene sheets during the hot season. There are advantages to using solarization: specifically, it is a simple, non-chemical, non-hazardous method

that avoids the use of any toxic materials, does not contaminate the site, and is, therefore, suited to organic farming or other low-input agricultural systems. As global environmental quality considerations grow in importance, along with an increasing human population, evolving concepts, such as soil solarization and other uses of solar energy in agriculture, will become more important (Ashrafi *et al.*, 2009).

Ashrafi *et al*. (2009) observed that solarization was accomplished by the application of clear polyethylene sheets to moist soil for 63 days during the hot season. The treatment increased maximum soil temperature by around 15 ºC, and at 5 cm below the soil surface, a temperature of more than 45 ºC was reached for 34 to 60 days whereas this temperature was not reached at all in the first season and not for 20 days (second season) in unmulched soil. In solarized soil, no broomrape shoots emerged, and neither haustoria's nor underground tubercles of the parasite were found on cucumber roots. The treatment killed about 95 per cent of buried viable seed, and induced secondary dormancy in the remaining per cent. In non-solarized plots, broomrape shoots were still present at a high density, decreasing the plant growth and fruit production. Fruit yield was 33 to 88 per cent higher in the solarized as compared with the non-solarized treatment.

Solarisation is a technique of control, not eradication. Solarisation may be more effective if combined with added nitrogen fertilisers; this can dramatically improve the kill of Orobanche seed at greater depths. Therefore, combination of solarization (2-6 weeks) and chicken manure at all depths (0, 5, 10 cm) is an effective weed management to control Orobanche and suppress the infestation, and growth of other weeds in subsequent planting of cabbage. Chicken manure, however, significantly increased the yield of cabbage (Haidar and Sidahmed, 2000).

4. Chemical methods

Suicidal germination by application of synthetic strigolactones to the soil and other germination stimulants:The seeds of broomrape require chemical signals from the host root to germinate, the use of chemicals with the ability to stimulate broomrape seed germination in the absence of a suitable host may lead to a reduction in the *Orobanche* seed bank. This is "suicidal" germination because; once germinated, the *Orobanche* seeds cannot return to dormancy and cannot survive for longer than a few days without nutritional supply from a host. This is an ideal control strategy, but its utility is limited in real-world applications. Initial attempts to deplete broomrape seed banks using synthetic Strigolactone were made by using the synthetic Strigolactone analogue GR7 (Fernández-Aparicio *et al.* 2011). However, field application of these GR type Strigolactones provided only partial control of Orobanche owing to the instability of the compound, particularly at pH >7.5 (Fernández-Aparicio *et al.*, 2011), which is common in *Orobanche*-infested soils. The lack of proper formulation for field application of these compounds also contributed to the fact that this approach was considered unrealistic. Optimization of formulation and field application protocols for new GR-type Strigolactones such as Nijmegen-1 has recently allowed promising levels of *Orobanche ramosa* L. reduction (Zwanenburg *et al.* 2009). New Strigolactone analogues are continuously being produced (Mwakaboko and Zwanenburg 2011), and these could serve as candidates for the suicidal germination approach, as long as they can be properly formulated for field application. Environmental side effects of synthetic Strigolactone applications have not been sufficiently studied. As Strigolactones are active in broomrape seed germination at low concentrations, side effects to the environment would be expected to be low. However, research has shown other functions of Strigolactones in the rhizosphere, including that Strigolactones promote hyphal branching in *Arbuscular Mycorrhiza* Fungi, rhizobial nodulation (Soto *et al.* 2010), development and ecophysiological processes in mosses through quorum sensing-like

signal, germination of dormant weed seeds, growth of phytopathogenic fungi and asymmetric root growth and inhibition of root hair elongation in the host. Additional functions and effects of Strigolactones are expected to be identified shortly (Xie *et al.* 2010). Thus, the direct application of high levels of synthetic Strigolactones could have unwanted side effects on beneficial microorganisms such as mycorrhizal fungi, which could suffer from uncontrolled branching, or Strigolactones could alter ecophysiological process in bacterial communities or crops themselves by altering physiology and morphology. In addition, synergism may occur between applied Strigolactones and the natural stimulants released by the crop, leading to an increase in both parasitic weed seed germination and host infection. Plakhine *et al.* (2009) reported that a few months following the application of Nijmegen-1 to *Orobanche*-infested soil, levels of host plant infection by the parasite increased significantly.

Although ethylene biosynthesis has been reported to be required for the induction of *O. ramosa* germination, exogenous application of ethylene is not effective in inducing the germination of *Orobanche*. Unlike Strigolactone, guaianolide sesquiterpene lactones present in Asteraceae species are not derived from the carotenoid pathway and are the main germination stimulants in the rhizosphere of sunflower roots acting specifically in seeds of *Orobanche cumana* Wallr. (Joel *et al.* 2011). Studies of structure–activity relationships have led to the finding that the introduction of a second lactone moiety in its structure (guaianestrigolactones) produced activity against other *Orobanche* species. Although Brassica species are known to produce Strigolactone (Goldwasser *et al.* 2008), and Strigolactones are known to induce germination of *O. ramosa* (Fernández-Aparicio *et al. 2011),* isothiocyanates rather than SLs are now believed to play a major role in *O. ramosa* stimulation in *Brassica napus* L. (Auger *et al.* 2011). However, iTCs might play a dual role in *O. ramosa* germination. Thus, the research reported that low concentrations (0.1–10 mg.L^{-1}) of phenyl iTC and allyl iTC (i.e., 2-propenyl iTC) stimulate *O. ramosa* germination, whereas higher

concentrations (100–1000 mg.L^{-1}) have an inhibitory effect. Commercial soil fumigants metham sodium and dazomet are based on the release of methyl iTC. The Australian Branched Broomrape Eradication Program is focusing on using dazomet (120–350 kg.ha^{-1}) (Virtue *et al*.2006). In addition to the iTC compounds, other non-Strigolactone root exuded compounds, or just non- Strigolactone compounds have been shown to have a role in broomrape germination. A number of compounds have been identified in pea root exudates, including peagol, peagoldione, and peapolyphenols A–C together with a chalcone, which selectively stimulate *Orobanche* seed germination. Also, a triterpene and a sterol, identified as soyasapogenol B and trans-22-dehydrocampesterol, have recently been isolated from common vetch root exudates. Soyasapogenol B stimulates germination of *Orobanche minor* Sm. seeds only, whereas trans-22-dehydrocampesterol stimulates *Orobanche aegyptiaca* Pers., *Orobanche crenata* Forssk., *Orobanche foetida* Poir., and *O. minor* (Evidente *et al*. 2011).

Chemical control of broomrape has been extensively explored since the 1970s. However, this form of control is complicated by a number of factors including: (i) it is effective only as a prophylactic treatment, since in most cases we do not know the infestation level; (ii) the parasite is directly connected to the host; (iii) if the herbicide is to be applied to the parasite through the conductive tissues of its host, the host must be selective to the herbicide without reducing its phytotoxicity; (iv) the parasite can often continuously germinate throughout the season, developing new infections (Perez-de-Luque *et al.*, 2010).

The herbicides that are currently in use for broomrape control are glyphosate, and herbicides belonging to the imidazolinones (Eizenberg *et al*., 2006a) or sulfonylureas. Glyphosate disrupts the biosynthesis of aromatic amino acids inhibiting the key enzyme 5-enolpyruvylshikimate-3-phosphate (EPSP). Imidazolinones and sulfonylurea herbicides inhibit acetolectate synthase (ALS), also called acetohydroxyacid synthase (AHAS), a key enzyme in the biosynthesis of the brand-chain amino acids isoleucine, leucine and valine. All of them are systemic herbicides absorbed through foliage and roots of plants with rapid translocation to the attached parasite, which acts as a strong sink (Colquhoun *et al.*, 2006).

Regarding field crops, three different methods of herbicide application can be considered: foliar application, soil application and seed treatments. With foliar applications, broomrape underground development stages should be monitored because control is ineffective if the attachments are too large. On the other hand, if the herbicide is applied too early, not enough attachments will be controlled. Foliar herbicide application for broomrape control normally requires lower herbicide rates. Sequential foliar application of low rates of glyphosate could be effective for broomrape control only on a few hosts in the families *Apiaceae, Fabaceae* and *Brassicaceae.* Imazapic applied to foliage for broomrape control is effective in sunflower (*Helianthus annuus*), carrot (*Daucus carota*), parsley (*Petroselinum crispum*), faba bean (*Vicia faba*), celery (*Apium graveolens*) and vetch (*Vicia* spp.). Both pre and post-crop emergence treatments with imazethapyr have effectively protected peas against broomrape damage, with consequent increases in yield. In some cases, herbicides control the parasite but are only moderately selective to the host, e.g. imazapic did not inhibit the vegetative growth of sunflower, but high rates of application of the herbicide in the initial sunflower inflorescences stage injured the reproductive production of sunflower.

In heavy infested broomrape fields (*Orobanche cernua* Loefl.) in tomato (*Lycopersicon esculentum* Mill.), application of sulfosulfuron at 75 g a.i. ha^{-1} was effective in preventing the development of broomrape and reducing the seed inoculum potential in the soil by registering significantly lowest broomrape number, spike height, spike dry weight with higher broomrape control efficiency, which also accounted for higher tomato plant height, number of branches, leaf area plant^{-1} at harvest, higher fruit weight plant^{-1} and fruit yield of tomato (Dinesha *et al.*, 2012).

Soil applications of sulfonylurea herbicides effectively control broomrape in tomato (*Solanum lycopersicum*) and in potato (Eizenberg *et al*., 2006b), by killing pre-conditioned seeds or young attachments.

Seed treatments with imidazolinones have proven to be effective for controlling *O. crenata* in faba bean. The great advantage of this method is the low cost of application. The herbicide is incorporated as a coating on the seeds and distributed with them at the time of planting. Using seed coating required high specificity between host and parasite, therefore it is not wide-spread. This replaces a pre-emergence treatment and saves mechanical application costs. In addition, the application of imidazolinones reduces the herbicide rate required by two to three folds, hence being less harmful to the environment. However, under favourable environmental conditions for broomrape attack, the treatment must be supplemented to obtain high broomrape control.

Coating sunflower seed with 2 kg a.i ha^{-1} and soaking the seeds in 50 per cent a.i of pronamide has lowered broomrape shoot dry weight and increased the yield of sunflower from 2141(control) to 2849 kg ha^{-1} in coated seed and from 1240 (control) to 1795 kg ha^{-1} in soaked seeds (Sanchez J. *et al*. 2003)

The sulfonylureas also have the advantage of selectivity for preventing emergence of broomrape growing on broad leaved weeds in a non-host cereal crop: 3 g ha^{-1} metsulfuron-methyl, 15 g ha^{-1} chlorsulfuron or 22.5 g ha^{-1} triasulfuron gave 100 per cent control of *O. ramosa* without damage to wheat or barley crops (Matthews, 2002). This may be due both to their direct effect on Orobanche and to their reduction of broad leaved weed hosts.

Goldwasser *et al*. (2000) observed that, in greenhouse and field experiments, *O. aegyptiaca* and *O. ramosa* were controlled in potato-infested soils by split foliar applications of low rates of the herbicides imazapic and rimsulfuron. Three doses of imazapic at 4.5 g ha^{-1} each, sprayed 2 weeks after crop emergence and re-applied at 2 weeks intervals, prevented *Orobanche* infestation.

Seed dressing with herbicides using ALS inhibitor slow release formulations of fertilizers, pesticides, and drugs are common. The principle of this technique is the development of biodegradable formulations for seed dressing with small amounts of herbicide for broomrape control. The slow -release herbicide formulations will achieve longer control of *Orobanche* with the ALS inhibitor imazapyr. The seed dressing allows imazapyr to spread throughout the crop root zone as the roots grow, prevents imazapyr from leaching away from the host rhizosphere, and requires less herbicide (Kanampiu *et al.*, 2002).

Chemical control based on growing-degree-days (GDD); after establishment of the parasitic weed on the host roots, degeneration and death of the parasite is the main factor that determines the host resistance. In sunflower, higher temperature was correlated with degeneration and death of more *Orobanche* tubercles increasing resistance in some varieties (Eizenberg *et al.*, 2003a).

A field study confirmed that GDD could be a predictive parameter for O. minor parasitism. Parasitism of *O. minor* in red clover could be predicted by growing-degree-days (GDD) under controlled conditions. This model was validated under field conditions (Eizenberg *et al.* 2005). Therefore, a predictive model may be a base for developing a decision-support system for chemical control (suitable timing for precise chemical control) of the parasite.

In investigation carried out in Palestine, three herbicides; chlorsulfuron, triasulfuron and imazaquin were tested to evaluate their efficiency in controlling the tomato broomrape. The herbicides significantly reduced the broomrape parasitizing tomato plants growing in pots, irrigated open field and under greenhouse conditions as foliar spray at the concentrations (0.5-10 μg.ml^{-1}) without visible injury effect on the plants. The foliar application of herbicides were able to increase the

broomrape dead spikes attached to the tomato plants at the concentrations (3-5 μg.ml^{-1}) without visible negative effect on tomato plants (Ibrahim *et al.*, 2012). In some situations, low rates of herbicide can control broomrapes when applied to the host crop. This has the attraction of allowing cropping on infested land, but rates and timing must be precise to prevent broomrape emergence. There is also the risk of developing resistance when low rates of the same herbicide are applied to a weed population in successive years.

5. Agronomic methods

5.1. Sowing date

Germination of *Orobanche crenata* tends to be very much reduced below 8 °C and further development is greatly reduced at low temperatures. Delaying the planting date affects *Orobanche* more than its hosts; the delay should be two weeks only from the date optimal for sowing in an uninfested field. However, this method must be adapted for different regions and for different hosts. Earlier planting dates are beneficial in certain instances. The change of the sowing date seems not to be very promising due to uncertainty of the environmental conditions, specifically temperature and rainfall situation. Farmer's negative perception to this method is controlled by the inherent traditional soil preparation which is largely linked to the onset of rain, and to the market demand for the produce.

Abundant experimental evidence in faba bean shows that shifting sowing from October to November, December or January reduces numbers and dry weight of attached and emerged broomrapes, both *O. crenata* and *O. foetida* (Grenz *et al.*, 2005a). Two factors are known to reduce parasite damage in late-sown crops: (i) decreased *O. crenata* germination due to suboptimal soil temperatures and (ii) obstructed *O. crenata* development during underground stages. Since faba bean development is less susceptible to low temperatures and can be accelerated by increasing day-

length, pods enter the critical phase of rapid biomass accumulation relatively earlier than parasites. As a result, more parasites and lesser pods are aborted (Grenz *et al*., 2005a) observed a more pronounced effect of late sowing in dry years, which also may indicate the existence of soil moisture-driven effects.

5.2. Soil management

Management of the soil can strongly affect the seed bank, including broomrape seeds. Trench ploughing 45-50 cm deep with a mouldboard plough reduced *O. ramosa* by 80-90 per cent in tobacco fields of Eastern Europe by burying seed to depths where it is unlikely to germinate. This method would have limited usefulness here due to the risk of drift on light soils and the need to follow up with minimum tillage for several years. Minimum tillage can contribute to broomrape control by reducing the amount of viable seeds incorporated into the soil.

Nitrogen compound application and manure fertilization also appear to be candidates for putative control of broomrapes: some studies have shown that nitrogen in ammonium form negatively affects broomrape germination and/or elongation of the seedling radical. In addition, manure fertilization augments the killing effect of solarization on *O. crenata* seeds (Haidar and Sidahmed, 2000).

5.3. Hand weeding

Weeding of Orobanche is mainly accomplished after the parasitic damage has already been done. It is not likely to show any yield increase in the short term. Weeding is laborious and time-consuming, and not very promising in highly infested areas. However, in combination with other methods, it can reduce the seed bank very efficiently (FAO, 208).

5.4. Intercropping

Intercropping is a method facilitating simultaneous crop production and soil fertility building. There is a renewed interest in intercropping linked to the need for

reducing nitrogen cost and soil erosion. Intercropping is already used in regions of Africa as a low-cost technology of controlling the broomrapes (Oswald *et al*., 2002).

Recently it has been demonstrated that intercrops with cereals or with fenugreek or berseem clover can reduce *O. crenata* infection on faba bean and pea due to allelopathic interactions (Fernandez-Aparicio *et al*., 2010). This has been confirmed in a subsequent study, in which trigoxazonane was identified in the root exudates of fenugreek which may be responsible for the inhibition of O. crenata seed germination (Evidente *et al.*, 2007).

Maize and snap bean as potential trap crops on Orobanche soil seed bank showed better performance in stimulating germination of *Orobanche* seed bank and raised the germination by 74 and 71 per cent, respectively. Maize and Snap bean were also complementing each other under inter-cropping and soil seed bank of *O. ramosa* and *O. cernua* was depleted by 72.5 per cent per season. Yield of tomato was significantly increased due to the reduction of Orobanche seed bank in the 3rd season (2004) (Girma *et al*., 2005).

Field experiments noticed that *O. crenata* infection on faba bean and pea is reduced when these host crops are intercropped with oat. The number of *O. crenata* plants per host plant decreased as the proportion of oats increased in the intercrop. Pot and rhizotron experiments confirmed the reduction of infection in faba bean intercropped with cereals. It is suggested that inhibition of *O. crenata* seed germination by allelochemicals released by cereal roots is the mechanism for reduction of *O. crenata* infection (Fernández-Aparicio *et al*., 2013).

5.5. Crop rotations

Rotation with non-host crops is usually suggested. The use of trap crops offers the advantage of preferentially stimulating broomrape suicidal germination. Flax, fenugreek and Egyptian clover are established to be successful trap crops for *O. crenata.* There are claims that a reduction in infestation has been reported in rotations with rice, due to water flooding (Sauerborn and Saxena, 1986), however, this has not been substantiated. The incorporation of resistant legumes in crop rotations may also maintain broomrape infestation at low levels.

Gawahir (2006) reported that Infestation of *Orobanche* decreased by 37 per cent at Elgeli/Sudan under the crop sequence of onion-onion onion-tomato where tomatoes yield was increased by 38 per cent. At Alafoon/Sudan crop sequence of onion-onion-onion/tomato and/or onion-alfalfa-alfalfa-tomato decreased *Orobanche* infestation by 90-95 per cent and the yield of tomato was increased by 60 per cent. Crop sequences in the two locations, in addition to increase of tomato yield, decreased the *Orobanche* incidence, branching and seed production.

Acharya *et al*. (2002) noticed that a local cultivar of *Brassica campestris* has been used as a catch crop in Nepal, reducing the *O. aegyptiaca* seed bank by around 33.35 per cent.

Experimental results in Tehran indicated that using trap crops namely sesame, brown indian-hemp, and common flax and black-eyed pea decreased broomrape biomass by 86, 85.3, 75.2, and 74.4 per cent, respectively. Reducing broomrape biomass caused increases in the tomato yield. Meanwhile, sesame, brown Indianhemp, Egyptian clover and mungbean increased total biomass of tomato by 71.4, 67.5, 65.5, and 62.5 per cent, respectively. It was observed that these plants have a great potential to reduce broomrape damage and they can be used in rotation in broomrape infested fields (Sirwan *et al.*, 2010).

In Tunisia, the results suggested that in fields infested with *O. foetida*, the use of bean, pea, flax and fenugreek in the crop rotation may reduce the *Orobanche* seed bank. This has been confirmed by experiments showing the pea stimulates germination of *O. foetida*

seeds but is resistant to infection, therefore, reducing seed bank (Fernández-Aparicio *et al*., 2011). Whereas in fields infested with *O. crenata*, crops such as bean, flax, alfalfa, wheat and oat used in the crop rotation may reduce the soil seed bank of this broomrape (Abbes, 2008).

5.6. Fertilization

Orobanche tends to be associated with less fertile soil conditions. High levels of nitrogen fertilizer or chicken manure showed a suppressive effect.

Mesbah *et al*. 2012 reported that with increasing of nitrogen fertilizers concentration, studied indices (bush height of sunflower, fresh weight of stem, leaf and crop of sunflower) were increased. In the other side, with increasing of nitrogenous fertilizer, the amount of broomrape germination was decreased. In interaction of type of nitrogenous fertilizers and amount of nitrogenous fertilizer, the maximum yield of sunflower seed in the concentration of 5 ppm of urea fertilizer was obtained. The minimum amount of broomrape germination also was obtained from the concentration of 5 ppm of urea fertilizer.

Urea at 276 and 207 kg N ha^{-1}, ammonium nitrate, and ammonium sulfate at 207 kg N ha^{-1} and the goat manure at 20 and 30 t ha^{-1} were found to be most effective in reducing parasitism of *Orobanche* and enhancing growth of tomato plants. Even though drastic reduction of broomrape infestation was obtained, ammonium nitrate and ammonium sulfate at 276 kg N ha^{-1} seemed to be injurious to tomato plants. As nitrogen rates increased, the numbers and dry weights of shoot of branched broomrape decreased and the yields of tomato increased linearly except the yields obtained from the highest rate of ammonium nitrate and ammonium sulfate. This result indicated that broomrape infestation of tomato decreased with increases of soil nitrogen (Mariam and Rungsit, 2004). The mixtures of chicken manure (20 t ha^{-1}) and sulphur (0, 1, 4, 8, and 12 t ha^{-1}) at all tested rates significantly reduced the dry weight of *Orobanche* and increased

eggplant and potato yield compared with the control (Haidar and Sidahmed, 2006).

6. Biological methods

Like all other plants, broomrapes have natural enemies which can affect their growth and can potentially be used as agents for their control. Biological control of weeds is defined as the use of natural antagonists to exert pressure on the population of their host to reduce it to levels below economic importance. Unlike chemical compounds, biological control agents have the advantage of being specific to the weed, and do not directly contribute to environmental pollution.

This technique utilizes living organisms (insects, fungi, viruses, bacteria etc.) to suppress or reduce broomrape infestation. Pathogenicity toward non-target plants is a major constraint; therefore, it is very important that host-specificity and risk assessment should be made before the release of a control organism into the environment.

The 'bioherbicide approach' employs virulent strains of pathogens (viruses, bacteria or fungi) which naturally occur on the weed and enhances their destructive activity. The infection build-up of the pathogen is manipulated to the extent of causing significant damage to the parasitic weed. Pathogens can be used as sole agents or as part of a complex integrated control strategy (Sauerborn *et al*., 2007).

Biological control is particularly attractive in suppressing root parasitic weeds in annual crops because the intimate physiological relationship with their host plants makes it difficult to apply conventional weed control measures. Both insects and fungi have been isolated that attack parasitic angiosperms.

Most of the insects which have been reported to occur on *Orobanche* species are polyphagous without any host-specificity and thus damage to these parasitic weeds is limited (Klein and Kroschel, 2002). For biological

control, oligo- and monophagous herbivorous insects are of interest. The fly *Phytomyza orobanchia* (Diptera: Agromyzidae) is reported to be host-specific attacking only *Orobanche* species. Its distribution is related to the natural occurrence of *Orobanche* spp. and *Smicronyx* spp. (Coleoptera: Curculionidae). These insects prevent seed production through the development of larvae inside the seed capsules of their target hosts and thus contribute to reduce their reproductive capacity and spread. However, research with both insects has revealed that their effectiveness to prevent seed set is limited and will not be enough to lower the soil seed bank significantly (Klein and Kroschel, 2002).

A factor that may limit the effect of P. orobanchia and Smicronyx spp. is soil cultivation, especially deep ploughing. Hibernating pupae can be destroyed and/or buried and prevent insect emergence. Further limiting factors of cultivation are pesticide applications against crop pests if these coincide with the flight periods of the two beneficial insects. Moreover, Phytomyza and Smicronyx suffer from indigenous antagonists which may have an important impact on their population levels. Because of their short lifetime and enormous seed production and the vast damage caused to the host by unemerged plants, *Orobanche* cannot be regarded ideal organisms for biological control by insects. Approximately 30 fungal genera were reported to occur on *Orobanche* spp. (Boari and Vurro, 2004).

Soil-dwelling microorganisms have been specifically sampled, since they have a number of advantages in the control of root parasites: (i) they can provide effective control by attacking the seeds and the early stages of the developing parasite; (ii) they are less sensitive to the environmental conditions compared with aerial pathogens; and (iii) they are expected to survive in the soil by producing resting structures at population levels sufficient to provide residual control of the parasitic plant. Numerous microorganisms potentially useful for the biocontrol of *Orobanche* species have been isolated and reported, but none has been subject to continuous wide-spread use (Boari and Vurro, 2004).

Results of surveys for fungal pathogens of *Orobanche* revealed that *Fusarium* species were the most prominent ones associated with diseased broomrapes. Of these, *F. oxysporum* was the predominant species. *Fusarium* species as soil-borne fungi possess several advantages which render them suitable for the bioherbicide approach. In the soil they are relatively protected from environmental stress of drought and heat, frequently occurring in the area of distribution of *Orobanche*. The saprophytic nature of *Fusarium* spp. allows them to be cultured in liquid as well as solid media; and particularly the *formae* speciales of *F. oxysporum* are highly host-specific. Because most of the damage to host crops occurs while the parasitic weed is still underground, use of soil-borne biocontrol agents such as *Fusarium* spp. can add to improving crop yield by destroying the parasite at its early developmental stages. To date about six *Fusarium* species are reported to be associated with *Orobanche* (*F. arthrosporioides, F. nygamai, F. oxysporum, F. oxysporum f.*sp. *orthoceras, F. semitectum var. majus, F. solani*) have shown significant disease development in selected species of *Orobanche* (Shabana *et al.*, 2003) when tested under controlled and/or field conditions.

Under laboratory and greenhouse conditions excellent control was repeatedly observed with *F. oxysporum* f.sp. *orthoceras* against *O. cumana* on sunflower. The total number of *O. cumana* could be reduced by about 80 per cent after soil application of a simple granular formulation of the fungus. Cohen *et al.* (2002a) observed reduction in *O. aegyptiaca* attached to tomato in greenhouse experiments using host-specific strains of *F. oxysporum* and *F. arthrosporioides.*

Although data on the efficiency of *Fusarium* spp. to control *Orobanche* in the field are rare, the results already indicate that *Fusarium* spp. in most cases do not provide the level of control desired by farmers. Thus there has been no successfully demonstrated control of this weed using potential inundative bioherbicides. The question arises, how the efficacy of the pathogens can be improved under field conditions in order to fight the target organism (Sauerborn *et al.*, 2007).

In the novel approach strategy two or more pathogens are combined and applied before or after parasite emergence. Some applied fungal mixtures caused a significant reduction of the number of emerging *O. cumana* (Cohen *et al.*, 2002) observed reduction in *O. aegyptiaca* attached to tomato in greenhouse experiments using host-specific strains of *F. Oxysporum* and *F. arthrosporioides*.

The feasibility of this approach has been demonstrated in the control of *O. cumana* in sunflower (Dor *et al.*, 2003). A bioherbicide system was based on two fungal pathogens *F. oxysporum* f. sp. *orthoceras* and *F. solani* which had been isolated from *O. cumana* on sunflower and *O. aegyptiaca* on tomato, respectively. In pot trials, the pathogens gave a low control level when used individually but when applied as a mixture; both fungi caused a significant reduction of the number of emerged *O. cumana* and of the parasite's dry weight. The inoculum density of each fungus when applied alone was 105 colony forming units (cfu) ml^{-1}. The same inoculum level of each fungus was used with the mixture, thus resulting in an inoculum density of 2x105 cfu ml^{-1}.

Another approach, which only recently has shown to provide successful control of O. cumana, is to integrate the resistance inducer BTH (benzothiadiazole) with the bioherbicidal pathogen *F. oxysporum* f. sp. orthoceras. The combined treatment of the two agents resulted in highly reliable control of *O. cumana* and reduced the parasite's emergence up to 100 per cent (Müller-Stöver *et al.*, 2005). The excellent control level in the combined treatments resulted from a lower number and reduced dry weight of *O. cumana* shoots, indicating that the combination of control strategies takes effect already in the early developmental stages of the parasite. This could either be due to an enhanced activity of the fungus against the early underground stages of the parasite or to an enhanced induced resistance within the sunflower plant. In laboratory experiments, no enhancing effect of BTH on virulence and growth of the fungus has been observed so far.

Yet another approach which receives increasing attention is the engineering of hypervirulence genes into weed specific pathogens, e.g. genes which encode enzymes that degrade metabolites involved in crop defence mechanisms such as phytoalexines or coding for enhanced virulence by the production of fungal toxins (Gressel, 2004). To enhance virulence, two *Fusarium* species that attack *Orobanche* have been transformed with two genes of the indole-3-acetamide pathway that converts tryptophan into the plant hormone indoleacetic acid IAA, (Cohen *et al.*, 2002b). It was shown that overproduction of IAA provided a slight increase in virulence compared to the wild type but not enough to attain a satisfactory level of control. Extreme care should be taken with such genetically modified organisms due to their possible environmental impact, and fail-safe mechanisms should be installed and tested prior to release into the environment.

A synergized effect was found between *Fusarium oxysporum* f.sp. *orthoceras* and *Fusarium solani* on sunflower broomrape. Application of two fungi together to control sunflower broomrape was rusticated to the first weeks after application. Repeated applications are needed for adequate long season control. The development of fungal inocula application through drip irrigation system developed in Bari, Italy, opens new horizons in biological control methodology (Hershenhorn *et al.*, 2006).

Myrothecium verrucaria isolated from faba bean roots has been found to inhibit germination of *O. crenata* seeds due to the production of the macrocyclic trichothecene, verrucarin A (El-Kassas *et al.*, 2005). Preliminary results demonstrated control of infection of faba bean by *O. crenata* by the addition of spores of *M. verrucaria* to soil, raising the possibility that this approach might be applicable in the field.

Pseudomonas aeruginosa, Pseudomonas fluorescens, Bacillus atrophaeus, and *Bacillus subtilis* reduce the growth of *O. aegyptiaca* and *O. cernua* seed radicles that have previously been induced by GR24

(Barghouthi and Salman 2010). The fungus Myrothecium verrucaria isolated from the *O. crenata* – faba bean rhizosphere inhibits *O. crenata* germination in vitro (El-Kassas *et al.* 2004). Colonization by *Rhizobium leguminosarum* has been reported to decrease *O. crenata* seed germination (Mabrouk *et al.* 2007; Fernández-Aparicio *et al.* 2009b). Also, colonization by the nitrogen-fixing bacterium.

Azospirillum brasilense inhibits germination and radicle growth of *O. aegyptiaca* (Dadon *et al.* 2004). Colonization by AMF can also provide protection against parasitic weeds. For example pea reduced germination of various *Orobanche* and Phelipanche species (Fernández-Aparicio *et al.* 2010b), and tomato reduced *O. ramosa* germination (López-Ráez *et al.* 2011). Analysis of exudates of tomato roots using liquid chromatography – tandem mass spectrometry showed that Strogolactone production is significantly reduced upon AMF colonization (López-Ráez *et al.* 2011). The fact that AMF colonize roots of most agricultural and horticultural species and that AMF symbiosis reduces Strigolactone production by the host plant opens avenues for its exploitation as an environmentally friendly biocontrol strategy. Altered patterns in interactions between *O. crenata* and symbiotic mutants of *M. truncatula* and pea suggest that parasitic plant infection is controlled by both the conserved symbiotic pathway that mediates symbiont recognition and by the establishment and autoregulation mechanisms that regulate the extent of colonization by rhizobia and AMF (Kubo *et al.*2009; Fernández-Aparicio *et al.* 2010c). The *M. truncatula* genes "doesn't make infections", DMI2 and DMI3, which are required for both AM development and nodulation with Sinorhizobium meliloti (Catoira *et al.* 2000), play a negative function during *O. crenata* infection of *M. truncatula* and pea by limiting the number of infection events. This fact, together with the extreme conservation and structural complexity of the DMI2 protein in plant species, favours a more complex role of this pathway as a general switch of basal defence than initially thought. The autoregulation mechanism limiting host root colonization by the symbiont to below a detrimental level is part of the defence mechanism against parasitic plants, not only in *Lotus japonicus* L. (Kubo *et al.* 2009) but also in *M. truncatula* and pea (Fernández-Aparicio *et al.* 2010c).

7. Crop resistance

Goldwasser and Yoder (2001) assayed 50 different ecotypes of A. thaliana for their ability to induce *O. aegyptiaca* germination, and the "low germination stimulant" phenotype was not identified among them. In Arabidopsis,where natural resistance is not available, mutagenesis has proven successful in identifying resistant lines. In fact, 94 out of 13 000 A. thaliana fast neutron mutated M2 lines have been detected as low inducers of *O. aegyptiaca* germination

(Goldwasser and Yoder 2001). In tomato, the low germination stimulant phenotype has recently been reported in mutants owing to reduced exudation of trigolactones (Dor *et al.* 2011b) or the presence of germination inhibitors, as postulated in the wild tomato relative *Lycopersicon pennellii.*

With tobacco cultivars, mutants, or related Nicotiana species, little success has been made in identifying the source of resistance to *Orobanche* based on low induction of germination. In legumes, resistance to *O. crenata* associated with low induction of parasitic seed germination has been reported in several species (Pérez-de-Luque *et al.* 2005, Abbes *et al.* 2010), although it is not known whether this is based on production of germination inhibitors or on reduced production of stimulants. In pea, quantitative trait loci analyses revealed genomic regions involved in the control of low stimulation of *O. crenata* germination. Two quantitative trait loci were associated with pea roots that had low activity on inducing *O. crenata* seed germination (Fondevilla *et al.* 2010). Another preattachment mechanism could be related to the chemotropism responsible for the correct guidance of the *Orobanche* seedling towards the host root.

Misdirected growth of germinated *O. crenata* seeds within the potentially infective distance has been observed in pea (Pérez-de-Luque *et al*. 2005), probably owing to changes in the concentration of compounds exuded from host roots responsible for the chemotropic response of the seedlings , Excess SL exudation could also represent a resistance mechanism in which parasite radicle contact with the host root is avoided. Breeding programs focused on selection of host genotypes for high root exudation levels of germination stimulants could identify better candidates for trap crops to be used in a suicidal germination control strategy. Genetic variation in this trait has been observed in important cultivars such as soybean.

A novel chemical control strategy has been developed during the past few years: systemic acquired resistance (SAR). SAR can be induced in plants by the application of chemical agents. Recently it has been shown that SAR of host plants can be used for the control of important broomrape species (Sillero *et al*., 2012). However, research on the effects of SAR on host-Orobanche systems is still in its infancy. Application of the resistance inducing agent BION® (1,2,3-benzothiadiazole-7-carbothioic acid S-methyl ester, Syngenta) stimulates the production of defence mechanisms in sunflower roots, which protects against parasitism of *O. cumana* (Buschmann and Sauerborn, 2002). Recently, Fan *et al*. (2007) evaluated the effects of prohexadione-calcium (PHDC) on *O. cumana* seed germination and induction of sunflower resistance to this root parasitic weed, and showed retarded *O. cumana* tubercle formation and development. Despite no chemical agents were used.

Mabrouk *et al.* (2007c) have also shown that some *Rhizobium leguminosarum* strains decrease *O. crenata* infections in peas by inducing systemic resistance.

Resistance to broomrapes is a multi-faceted response in faba bean and legumes. Several defence mechanisms have been detected in plants resistant to broomrape attack, mainly involving cell wall reinforcement (Perez-de-Luque *et al*., 2005, 2006a, 2007), production of toxic compounds (Lozano *et al*., 2007) and sealing of vascular tissues (Perez-de-Luque *et al*., 2006b). Trap crops are commercially valuable crops that are able to reduce the seed bank of parasitic plants. They are false hosts owing to their ability to fool the parasite by triggering germination but not being compatible in the downstream infection process Promising results for trap crops have been reported for many host–parasite interactions, including pepper against *O. aegyptiaca* and *Orobanche cernua* Loefl. barley, birdsfoot trefoil, common vetch, creeping bentgrass, cucumber, field corn, red fescue, flax, Italian ryegrass, nasturtium, oats, orchardgrass, perennial ryegrass, snap bean, sugar pea, sunflower, sweet corn, tall fescue, tomato, and wheat against *O. minor* (Lins *et al.*2006); *Crotalaria juncea* L. and *Vigna radiate.* In addition to these annual trap crops, leguminous trees and shrubs such as *Sesbania sesban* (L.) Merr., *Senna* spp., *Crotalaria agatiflora.* Trap crops as a control technique should be included in the regular rotation and fallow management of infested fields and integrated with other control measures. Trap crops cannot be expected to eliminate the seed bank in the soil immediately.

Regarding faba bean, the mechanisms described to date are pre-haustorial, i.e. they are observed after attachment and penetration into the host tissues but prior to the development of the haustorium (the organ connecting both, the host and parasite vascular tissues). According to Perez-de-Luque *et al*. (2007), these defensive responses correspond to: (i) callose depositions in the host cell walls from the cortex and in contact with the parasite tissues, and (ii) lignification of host pericycle and endodermal cells. The second response (lignification) occurs after the obstruction of parasite intrusive cells in the host cortex has been overcome, and prevents further penetration into the central cylinder and formation of a haustorium.

In the last five decades, crop yields increased because of chemical control of weeds, especially with selective herbicides. Recently, unfortunately, herbicides have been removed from markets because of toxicity, weed resistance to the herbicides, and environmental

concerns (Gressel, 2004). Developing a new herbicide by chemical companies is difficult, time-consuming, and very expensive. Accordingly, there is a pressing need for biotech-derived crops (not only crops with engineered herbicide resistance adapted over the last few years), but also using newer technology based on genomic, protoomic, and metabolomic tools. Gressel (2004) described newer technologies that will assist in meeting the needs for herbicide-resistance crops. Notably, herbicides that are metabolized by transgenic plants, i.e., glufosinate (Basta®), which is metabolized by the bar gene in transformed plants before reaching the roots of transgenic-resistant crops, would be ineffective for parasitic weed control. Transgenic herbicide resistance may also pose food safety issues through the expression of the new gene in the crop plant. Concern may also arise regarding the possible gene transfer from transgenic crop plants to wild plants, although different ways to overcome these concerns have been proposed (Gressel, 2004). Therefore, these parameters should be taken into consideration while applying chemicals to herbicide-resistant crops. Aviv *et al.* (2002) engineered a mutant ALS gene into carrot, allowing the control of broomrape by imazapyr (an imidazolinone ALS inhibitor).

Several tobacco cultivars transformed with a mutant acetohydroxy acid synthase (AHAS) 3R gene (isolated from a sulfonylurea resistant *Brassica napus* cell line) were resistant to the herbicide chlorsulfuron (Slavov *et al.*, 2005). The effect of chlorsulfuron on broomrape was clearly demonstrated: A very low percentage (from 0.1 to 4 %) of its active ingredient that reached the plant roots was sufficient to kill the parasite at an early developmental stage after two treatments (Slavov *et al.*, 2005). Parasitic weeds will rapidly evolve resistance to herbicides because of their prolific seed production. Therefore, resistance to glyphosate, asulam, chlorosulfuron, or imazapyr will eventually appear. Therefore, herbicide resistance crops should be wisely used or combined with other control methods, and new resistant crops continually developed (Ali, 2007).

8. Integrated methods

Integrated control of broomrape weeds means to combine and to integrate different preventive measures and control instruments into the given farming system. (Table1) These are promising combinations for integrated *Orobanche* control in legume crops:

Lentil	Delayed sowing (Dec./Jan.) + genotype, adapted for late sowing (+ herbicide, depending on severity of field infestation)
Chickpea	Less infected variety (ILC 482); herbicide (imazethapyr 50g a.i./ha post-sowing) only if infestation of the site is heavy
Faba bean	Less infected or resistant variety (Spanish material) + imazethapyr 2 x 30g a.i./ha; imazethapyr 2 x 20g a.i./ha), or delayed sowing + herbicide
Narbon vetch	Less infected genotype (e.g. ICARDA acc. 578) + sowing delayed for two weeks (under heavy infestation: imazaquin 2 x 20g a.i./ha) in spring)
Vetch	Less infected genotype (e.g. ICARDA acc. 715) + sowing delayed for two weeks
Forage legumes	Less/not infected species (*Vicia dasycarpa*, *Lathyrus ochrus*), or delayed sowing + herbicide, or mowing for hay production followed by soil tillage
Field pea	Delayed sowing + herbicide (imazaquin 2 x 20g a.i./ha in spring)

Sulfosulfuron at a rate of 40 g. a.i. ha^{-1} applied 2-3 times in two-week intervals starting two weeks after planting followed by sprinkler irrigation of 300 m^3 ha^{-1} delays the appearance of broomrape inflorescences above ground by 3-4 weeks. Such a delay prevents the damage caused to the yield but not the continuation of the field contamination with broomrape seeds. Addition of an imidazolinone herbicide application such as imazapic or imazamox 63-70 days after planting prevents almost completely broomrape shoot emergence and seed setting of inflorescences present in the field during herbicide application (Hershenhorn *et al.*, 2006).

Mohammed *et al*. (2012) conducted experiment to assess the effect of combination of bacterial strains and chicken manures on broomrape on faba bean, the results displayed that among all treatments faba bean inoculated with TAL 1399 alone or in combinations with B*acillus megatherium var Phosphaticum* (BMP) or *Azospirillum brasiliense* (Ab) plus chicken manure at 35 g pot^{-1} displayed no *Orobanche* emergence (above the ground) until the end of experiment. Furthermore, crop treated with TAL 1399 plus chicken manure at 35 g pot^{-1} was significantly higher in root, shoot and total dry weight as compared to control and other treatments.

Three isolates of *Trichoderma* species including *T. harzianum* T1, *T. harzianum* T$_3$ and T. viride T$_2$ were tested for control of *Orobanche* species in peas, faba bean and tomatoes under field conditions in Egypt. Results of field studies showed that soil treatment with these three fungal agents alone or soil treatment with fungal agents plus aerial spray of glyphosate (50 ppm) was efficient and cost-effective method in reducing infection, minimizing the number of spikes parasitic on host plants and increasing yields of peas, faba bean and tomatoes (Mokhtar *et al*., 2009).

9. Conclusion

The principal conclusion to be drawn from these studies must be that no single technique provides complete control of *Orobanche*, and resorting to some of them is unavoidable. Physical methods are very useful to prevent the Orobanche but are tedious, time-consuming and costly. Chemical, agronomic control methods and host resistance appear to be the most appropriate measures when available and affordable. Moreover, some biological and crop resistance approaches are promising but they are too expensive and control may not be complete, by this, still need more research. It was claimed that integrated approaches combining several techniques could be more effective. However, these integrated programmes are practiced only on a small scale in a few countries because of cost and technical problems. While avoidance of dispersal of broomrape, crop resistance, and prevention measures could be effective and the most economical methods to reduce this root parasitic weed infestations in agricultural fields. Advantages of these approaches are no chemical applications and no need for additional labour or complicated management, expensive equipment, or instrumentation, low cost, environmental safety, and may deplete the parasite soil seed bank. It is important both to assess the most severely infested areas in order to target these control measures most effectively, and maintain the seed bank of less infested areas beneath a threshold level of damage.

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