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Review Article

The weed *Orobanche*: species distribution, diversity, biology and management

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ABSTRACT

Weeds are ubiquitous and eternal pests. In India, the total annual loss of agricultural produce by weeds, insects, diseases and other pests are estimated to be 37%, 29%, 22% and 12%, respectively. Weeds are, mainly, autotrophs, but few are heterotrophs/parasitic such as *Orobanche/ Phelipanche sp* (Broomrape). Several species that are dominant across the world are *Orobanche cernua*, *Orobanche crenata, Phelipanche ramosa, Phelipanche aegyptiaca, Orobanche cumana,* and *Phelipanche muteli. Orobanche* is an important holo-root parasitic weed and cause yield losses of many economically important crops. The damage by *Orobanche* can range from 0-100%. Studies highlighted annual crop losses due to *Orobanche* infestation was to the tune of $1.3 to 2.6 billion worldwide. A *Orobanche* plant can produce more than 500,000 seeds, whose longevity may vary from 2-20 years. The distribution, species diversity and biology of this weed have been discussed in this review. Sound management strategies involving physical, cultural, biological and chemical options, and above all, integrated *Orobanche* management have been contemplated as well. New bio-technological approach that must trigger to develop host plant's resistance against *Orobanche* and recommended selective herbicides should be envisaged for better *Orobanche* management.

Introduction

Weeds are the most underestimated crop pest in tropical agriculture (McErlich and Boydston, 2014). Weeds pose tremendous challenge for successful crop production and their management costs higher than that of other agro-practices. Cultivated soils contain huge seed bank of weeds, which triggers germination of plenty of weeds. If weeds are left uncontrolled, become a serious

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menace in crop fields. Weeds are ubiquitous and eternal pests (Das, 2008). Of the total annual loss of agricultural produce from various pests in India, weeds roughly account for 37%, insects for 29%, diseases for 22% and other pests for 12% (Yaduraju, 2006).

Weeds are, mainly, autotrophs, but a few weeds are heterotrophs/parasitic. Parasitism occurs in at least 17 different botanical families (Das, 2008). Parasitic weeds are classified on the basis of parasitism on roots and shoots. They can be total-/holo-root parasites and partial-/hemi-root parasites on the basis of root-parasitism. Similarly, they are total-/holo-stem parasite and partial-/hemi stem parasite based on shoot/stem parasitism. Among different parasitic weeds, *Orobanche/Phelipanche* spp is most difficult to control because of its underground location, lack of photosynthesis, late appearance of parasitic shoots and complex mechanisms of seed dispersal, germination, and longevity (Foy et al., 1989). The weed broomrape (*Orobanche/Phelipanche* spp) is obligate, holo-parasite and attacks the roots of many economically important crops, such as rapeseed and mustard, brinjal, tomato, sunflower, tobacco and faba bean in the semi-arid regions of the world (Wickett et al. 2011). *Orobanche* attaches itself to the host plants, and strongly competes with them for water, nutrients, space and other resources. This leads to moisture and nutrients starvation in host crops and causes significant reduction in yield. The seeds of *Orobanche* spp contain little food reserves (~endosperm) by which they can hardly survive after germination. Immediately, the seeds which are in close proximity (within ≤ 1 mm distance) from the host roots try to establish a xylem connection with the host roots (Matusova et al. 2005). It germinates only when host roots exude certain chemical stimulants that promote chemotropic growth in the germ tubes (~radicles) towards host roots. The germinating *Orobanche* seed produces radicle, which elongates chemotropically and forms a haustorium, which gets strongly attached to the vascular system of host plant (Parker, 2012). Its mode of damage is mostly direct that causes significant losses in yield and quality of produce. Besides, certain specific characteristics such as host-specificity, wide-spread occurrence, competitiveness and aggressiveness with the host plants, prolific seed production, and prolonged seed viability make parasitic *Orobanche* spp very difficult to be controlled by normal weed management practices. Lack of effective control measures of *Orobanche* hastens its spread and makes soil sick over a small period with *Orobanche*. *Orobanche* species have strong adaptation mechanisms to co-exist with their hosts in the same environment, resulting in strong parasitism. Majority of crop plants lack internal resistance to *Orobanche* that adds to the problem and makes a vast number of crops susceptible (Rathore et al. 2014). Depending upon the extent of infestation, environmental conditions, soil fertility, and crops' competitiveness, the damage caused by *Orobanche* can range from 0 to 100% (Dhanapal et al. 1996). This poses a serious economic concern and necessitates effective management of *Orobanche* in crops.

Distribution

The infestations of *Orobanche* occur in large number of crop hosts across the countries of the world. The hot and temperate regions of Northern Hemisphere, particularly the Mediterranean region are homelands of majority of broomrapes (Sauerborn, 1991). However, few species are also found in other parts of the globe. Countries, where severe crop losses have been reported due to different species of *Orobanche* (Parker, 2009) are: Russia, Ukraine, Turkey, Spain, Eastern Europe and Eastern Mediterranean (due to *Orobanche cumana)*; Pakistan, India, Nepal, Arabian Peninsula and Egypt (due to *Orobanche cernua);* Nepal, Cuba, Chile, France and Australia (due to *Phelipanche ramosa)*. Besides these single species dominance, several other species of *Orobanche* can also be found depending on crop hosts grown in a country.

Table 1: Worldwide distribution of *Orobanche* and yield losses in host crops

***Orobanche* species**	**Crop hosts**	**Yield loss**	**Countries**	**Reference**
Orobanche crenata	Faba bean	12-40%	Morocco, Portugal,Spain, Egypt, Cyprus, Iraq, Italy, Jordan	Sauerborn (1991)
Orobanche cumana	Sunflower	20-55%	Russia, Ukraine, Spain, Israel, China, Greece	Parker (1994)
Orobanche cernua	Solanaceous crops: tomato, tobacco, pepper and eggplant	Tomato (30-55%) Tobacco (25-50%)	Pakistan, India, Nepal, Iran, Arabian Peninsula and Egypt	Parker (1994); Parker and Riches (1993)
Phelipanche ramosa	Solanaceous crops: tomato, potato and tobacco	Tobacco (10-50%) Tomato (30-80%, Chilli (80%)	Greece, Nepal, Cuba, Chile	Diaz et al. (2006); Parker (1994)
Phelipanche aegyptiaca	*Tori*, tobacco, potato, tomato, rapeseed, chickpea, vetch, water melon, muskmelon	Mustard, tobacco, potato, *Tori* (20-40%) Musk melon and water melon (20-70%)	Eastern Mediterranean through to Afghanistan, Pakistan, India and Nepal	Khattri et al. (2002); Shekhawat et al. (2012a)

In India, *Orobanche/Phelipanche* is widely distributed in the States of Karnataka, Andhra Pradesh, Tamil Nadu, Gujarat, Maharashtra, Madhya Pradesh, Rajasthan, Punjab, western Uttar Pradesh and Haryana, and a cause of great concern among the farmers. However, its heavy infestation is localized in northern Rajasthan, Haryana, Punjab, and North-East Madhya Pradesh, growing rapeseed and mustard in large areas. *Orobanche* infests about 90% area under tobacco in

Karnataka and causes 50-60% yield losses in some areas (Dhanapal et al. 1998). Similarly, it causes infestations in about 50% areas of tobacco (~40,000 ha) in Andhra Pradesh and cause nearly 50% crop yield losses. Besides, some tobacco growing areas of Tamil Nadu, Gujarat and Maharashtra also encounter higher yield losses due to heavy infestations of *Orobanche* spp. In the Mewat and Bhiwani districts of Haryana, tomato, brinjal, cauliflower and cabbage crops have been found infested with *Orobanche* spp (Punia, 2014). There is need to adopt location-based crop hosts-specific strategies for effective management of *Orobanche*.

Orobanche **species diversity and host range**

There are about 140 species of *Orobanche*, which attack cultivated crops, wild plant species, and weeds. Most species of *Orobanche* have multiple hosts, and one crop host can be infected by multiple species of *Orobanche*. The single genus of *Orobanche* is separated into two genera *Phelipanche* and *Orobanche* by morphological, karyological and phylogenetic tools (Joel, 2009). Most species of the *Orobanche* are unbranched except *Phelipanche ramosa*, which has branched stem. *Phelipanche ramosa* is a branched broomrape and native to central and south-western Europe, but is widely naturalized elsewhere. It is considered as a major threat to many commercial crops. In heavily infested areas, branched broomrape can cause total crop failure. The species that usually occur in India are *Orobanche cernua*, *Phelipanche ramosa, Phelipanche aegyptiaca, Orobanche cumana, and Phelipanche muteli*. They attack and parasitize a large number of dicotyledonous crops like tomato, potato, tobacco, egg plant/brinjal, fababean, groundnut, sunflower, safflower, niger, lettuce, rapeseed and mustard, cabbage and linseed. There are a large number of wild plants/weed hosts of *Orobanche* species, for example, *Galinsoga parviflora*, and *Solanum nigrum* are hosts of *Phelipanche ramosa; Datura stramonium, Bidens biternata, Tagetes minuta* and *Xanthium* spp are hosts of *Orobanche minor*. Even a particular species of *Orobanche* (not characterized) has been found to occur on *Parthenium hysterophorus* in Ethiopia (Das et al. 2002). The species of *Orobanche* predominant across the world with their respective host range are: *Orobanche cernua* (nodding broomrape): tobacco, tomato, sunflower (mainly plants under solanaceae, lamiaceae); *Orobanche crenata*: faba bean, broad bean and other legumes (plants under fabaceae, apiaceae); *Phelipanche ramosa*: *brassicas*, carrot, cotton, sunflower, safflower, potato, tobacco, tomato, brinjal and other solanaceous crops (under solanaceae, fabaceae, brassicaceae, cucurbitaceae, asteraceae, apiaceae, cannabinaceae, linaceae); *Phelipanche aegyptiaca* (Egyptian broomrape): almost same host range as in *Phelipanche ramosa*; *Orobanche minor*: tomato, *Brassicas* (under brassicaceae, solanaceae); *Phelipanche muteli*: brinjal, tobacco, tomato (under solanaceae) and *Orobanche cumana* Wallr. (sunflower broomrape): sunflower, clover, alfalfa (under asteraceae, fabaceae).

Orobanche **biology**

Orobanche is an achlorophyllous (devoid of chlorophyll), phanerogamic, heterotrophic, total-/holo-root parasite, and annual plant with fleshy, pale, reddish-brown or yellowish-brown, pubescent stem bearing a simple spike or raceme of flowers. The spike is loosely flowered, interrupted below and continuous above. Flowers are 1-2 cm long with petals united into a broad tubular corolla, 2-lobed upper lip and 3-lobed lower lip with spike inflorescence. The leaves are scale-like, sometimes ovate or lanceolate, 6-20 mm long, acute and sessile. *Orobanche* sp usually grows to a height of 50-60 cm above the ground. The flower colour varies with the species, with a fruit capsule which splits into two parts when ripe. It is cross-pollinated by bumble bee. Also, it has been estimated that a single broomrape plant can release more than 500,000 seeds, which can remain viable for decades in the soil (Habimana et al. 2014). Seeds are minute (size 0.3 × 0.2 mm and test weight/1000 seed weight is about (0.1-3.0 g), ovoid, reticulate and dust-like, which are easily dispersed by wind, water, birds, farm animals, manure and others. Seed longevity varies from 2-20 years.

Germination, infection/attachment and symptoms

Orobanche seeds require 1-2 weeks pre-conditioning period before it responds to host root exudates/ stimulants and one week stimulation from host root exudates for germination. If pre-conditioning or stimulant exudation is not proper, the seeds do not germinate and can remain dormant and viable in soil for about 10-12 years. Germination of *Orobanche* seeds may be induced by seed pre-conditioning followed by host root exudation within the soil up to 1 cm from the host roots. However, for optimum attachment the seeds have to be within 2-3 mm from host roots.

Attachment must occur within a few days of germination. The germinated seed produces a radicle up to 3-4 mm long with sticky papillae by which it adheres to the host root surface. A haustorium is a nutrient sucking structure, which penetrates host cells by enzymatic action resulting separation of the host cells. The haustorium swells up and forms fleshy clone (base) from which several “tubercles” or “nodules” develop. On a “tubercle/nodule” after 1-2 weeks a shoot bud differentiates and elongates to produce a shoot. Thus several tubercles develop into separate shoots, which emerge rapidly through soil and produce flowers within a few days after emergence. Secondary attachment points can also develop to connect *Orobanche* rootlets with host roots. Optimum temperature for germination is 20-25^{o}C. Higher pH (alkaline range) may inactivate the germination stimulant and reduce *Orobanche* germination. Soil type usually has no influence on germination, but *Orobanche* infestation is likely more on less fertile soils. Unlike *Striga*, *Orobanche* emerges through soil soon after forming haustoria.

Crop yield loss

The yield losses of most of the economically important crops like rapeseed & mustard, brinjal, tomato, sunflower, tobacco and faba bean occur due to *Orobanche* infestations in the semi-arid regions of the world (Wickett et al. 2011). The crop yield loss varies from crop to crop depending on the severity of *Orobanche* infestation. *Orobanche* species also vary in their potential to cause damage since morphology, height/stature, infection ability varies across the species. Singh et al. (1972) reported higher concentrations of acid-hydrolyzable and total carbohydrates in *Orobanche* than the host caused higher demand for sugars by the parasite (Singh et al. 1972). Orobanche always had a lower concentration of total soluble and total nitrogen than the host root. Therefore, they attack the developing roots of both young and mature plants and diversion of dry matter from host to the parasite occurs, which results in reduced biomass of host plant (Hibberd et al. 1999). In India, *Orobanche cernua*, *Orobanche cumana* and *Phelipanche aegyptiaca* are occurring on various crops such as tobacco, cumin, mustard, plantago, lentil, potato, brinjal and tomato and cause losses from 50% in tobacco to more than 80% in solanaceous vegetables (Punia, 2014). As the *Orobanche* entirely depends on host plants, at times it will be devastating where mono-cropping of solanaceous vegetables are grown in succession. Shekhawat et al. (2012b) estimated an average 28.2% reduction in the seed yield of Indian mustard with infestation of *Phelipanche aegyptiaca*. *P. aegyptiaca* with their haustorial cells penetrate crop roots and causes great damage to crops across the world. A significant reduction of around 15-49% has been recorded in the yield of mustard (Khattri, 1997; Akhter and Khan, 2018). Besides causing yield loss and reduction in cultivated area of crops, *Orobanche* also reduces crop quality (Parker and Riches, 1993; Lal et al. 2017). Ahmad et al. (2018) highlighted that worldwide annual crop losses as a result of broomrape infestation are estimated at about $1.3 to 2.6 billion. Refer to Table 1 for estimated worldwide yield loss and distribution of *Orobanche* species.

***Orobanche* Management**

Physical (manual and mechanical), chemical and biological methods of control of *Orobanche* and other weed species are the key to reducing infestation and yield losses of crops (Dhanapal et al., 1996; Shekhawat et al., 2017). Continued reliance on one type of control method will render it ineffective after some time; therefore, a multi-pronged approach must be undertaken for control of weeds in rapeseed and mustard. Some commonly practised weed management options are elucidated below:

Preventive measures

Prevention is employed for minimizing the spread of *Orobanche* across and within the regions as well as to reduce its soil seed bank on gradual basis. It includes the following measures.

Clean crop seed and farm hygiene

clean crop seed should be used, so as to reduce the spread of parasitic weed; farm implements (ploughs, hoes) from an infested field should be cleaned before taking them to a new field; quarantine should be followed properly; transfer of soil should be avoided from infested area to a non-infested area; grazing animals should be avoided in the infested area at least until the *Orobanche* has been removed; all pulled *Orobanche* plants should be destroyed by burning or burying immediately, otherwise, seeds may disperse from some plants if already matured; also *Orobanche* growing on wild hosts/weeds in and around crop fields should be destroyed with contact herbicide, such as paraquat, diquat to prevent its seed production.

Application of natural/synthetic stimulants

Ethylene does not stimulate *Orobanche* seed germination. However, several synthetic analogues of the natural stimulants, such as GR 7, GR 24 and GR 45 are available, which can induce *Orobanche* germination. They when applied well ahead of crop sown induce *Orobanche* germination, but the seedlings wither away in absence of a suitable host plant amounting to "suicidal germination", now called "honeypot strategy". The application of germination stimualnt leads to parasitic weed seed germination in absence of host with minimal chances of survival without host attachment (Macias et al. 2019). *Orobanche* plants those survived may be controlled by tillage, manual weeding or contact herbicide, *e.g*. paraquat, diquat. However, the combination of synthetic stimulants and trap crops towards *Orobanche* control would be the more effective option, if the stimulants do not jeopardize the germination of trap crops. Ground sunflower plants can also act as stimulant for *Orobanche* germination.

Physical (mechanical and manual) measures

The physical weed management options can be effective depending on crops and sites/locations. It should be advocated as complementary or supplementary measure with other options, preferably pre-emergence application of herbicides. The physical options may include the following options.

Soil solarization: It has been proved to be an effective measure for controlling annual weeds and few perennial weeds (Das and Yaduraju, 2001, 2008) and *Orobanche* (Haidar and Sidahmed, 2000; Das, 2008). The temperatures of 48-57ºC kill *Orobanche* seeds that are in the imbibed state; therefore soil must be wet at the time of treatment. Seeds of *Phelipanche ramosa* can survive 35 days at 50 ºC in dry air, but are quickly killed by temperatures of 40 ºC when wet. Solarization provides excellent control of *Orobanche* and ensures higher yield. The population of *Orobanche* and other weeds reduced significantly in the subsequent crops planted 6-12 months later. The effect is likely to reduce if deep cultivation follows. Soil solarization for a minimum period of 2 weeks during hot summer months (May and June in India) is also sufficient to control weeds, but it may be continued to several weeks together for prolonged effect (Singh et al., 2013). Soil solarization with 0.05 mm thick white polyethylene sheets for 30-60 days during hot summer although expensive can lower the menace by 60-90% (Asrafi et al. 2009). Higher cost economics although puts doubt on its large-scale application, it can be adopted in seedling-raising nurseries on small plots of land and for growing profitable cash crops like vegetables. In another study in Italy, soil solarization treatments reduced both *Orobanche* seed abundance and seed viability at 5 and 15 cm soil depth, with significant increase in seedbank dormancy (Mauro et al. 2015); Hand pulling: Usually periodical hand pulling of *Orobanche* shoots 3-4 times per season before seed setting is advocated in a bid to reduce maximum of its seed population for the coming years. Hand weeding although labour-intensive, is useful particularly under light infestations and should be practised as early as possible to avoid crop damage (Patel et al. 2017). It will facilitate crop plants to pick up faster growth, so that later emerging weeds can be smothered by canopy cover; Mulching: Spreading of residues of previous crops between the rows of succeeding crops may have several benefits such as weed control, moisture conservation and increase in organic matter in soil; Flooding: Flooding for a long period destroys viability/longevity of *Orobanche* seeds. A continuous flooding for about 1-2 month(s) prior to planting of tomato reduces *Orobanche* infestation in tomato. Similarly flooding required for rice can be utilized for controlling *Orobanche* in tobacco if rice is included in the rotation; Deep ploughing: Ploughing up to a depth of 20-25 cm during summer with normal interculture has been found effective towards reduction of *Orobanche* population and enhancement of tobacco yield in the following season (Khot et al. 1987). Also the implement SPEAR can be designed to remove tender *Orobanche* shoots.

Cultural measures

Cultural or ecological method of weed control exploits the crop's competitive behaviour, growing environment and crop management practices towards smothering of weeds. It is differently known as crop competition method (Das, 2008). It includes following options. Trap crops: Trap crops stimulate *Orobanche* seed germination, but the infections die either during filamentous stage (germinating seed with whitish radicle attached to host roots) or during the sub-terranean button sized growth stage without subsequent emergence into flowering shoots. Generally trap crops for *Orobanche* are pepper, sesame, cotton, soybean, lucerne/ alfalfa, clover, castor, rapeseed and mustard, linseed, maize, finger millet, cowpea, hemp, chicory, horsegram, sorghum, niger, brinjal, chick pea, which may be grown in rotation with host crops towards *Orobanche* control. Pepper (*Capsicum annuum* L.) is regarded as a more effective trap crop for a number of species of *Orobanche* particularly *Orobanche cernua*. Several sunflower cultivars also show potential as trap crops. Even ground sunflower stalks stimulate *Orobanche* germination. Lucerne, maize, clover, rapeseed, mustard, pepper and castor could be effective trap crops for *Phelipanche ramosa*; pepper for *Orobanche cernua*; and linseed for *Orobanche crenata*; Catch crops : Acharya et al. (2002) have used toria as a catch crop for *Orobanche* and observed 33.35 % reduction in seed bank of *Orobanche* with 2.1 g/m^2 of toria seeds; Time of sowing: Late planting likely reduces *Orobanche* infestation in tobacco and other crop hosts; Row planting *versus* broad-casting: Broadcast crop usually appears as a poor competitor against weeds and produces lesser yield than row-planted one because row planting maintains the required or near required population of crops with uniform plant distribution and facilitates easy adoption of weed control measures like hand-weeding, hoeing, inter-cultivation etc.; Crop rotation: Crop rotation with trap crops (which promote *Orobanche* seed germination but do not support parasitism) or catch crops (which support parasitism but destroy *Orobanche* prior to flowering) can effectively hinder new seed production and hence reduce soil seed bank. Crop rotation of mustard with non-host crops like wheat, barley, chickpea etc. is the most effective and commonly used management strategy for reducing the weed seed bank in heavily infested areas (Punia, 2014).

Maintain soil fertility

Orobanche is believed to infest more in soils of low fertility. Heavy dose of N fertilizer and higher soil fertility reduce *Orobanche* population. Therefore, N should be applied at least at the recommended rate if not possible at the higher doses on the ground of affordability by farmers and cost economics. *In situ* on-season green manuring as per the feasibility and applicability may be undertaken to maintain soil fertility. Green house experiments in Jordan and USA have enough established that higher concentration of nitrogen drastically reduces *Orobanche* infestation in several host crops. *Orobanche* germination is not much affected by N concentration in the solution, but its radicle elongation is severely inhibited. As a result, the chances for attachment to the host root get reduced. NH_4^+-N is reported more inhibitive than NO_3^--N probably due to NH_4^+ has some herbicidal effects. It is acidic or acid-forming fertilizer. Acidity nearby root rhizosphere of the host may induce inhibition to haustorium development and radicle elongation of *Orobanche*.

Biological measures

Biolgical weed control proves superior in controlling targeted problematic and invasive weeds in composite culture of weeds. It is also eco-friendly since it does not lead to environmental pollution. The biological agents are; Insects: Among a half-century insects feeding on the species of *Orobanche, Phytomyza orobanche* Kalt (family- Agromyzidae; order- Lepidoptera) offers a promise. It is native to the Mediterranean region, the main area of infestation. It is highly efficient against *Orobanche* because it is multivoltine (2-7 generations per season), which ensures repeated attack of the insects; the occurrence of adult flies greatly coincides with *Orobanche* shoot emergence/ infestation in the field; both adult and larvae are damaging to *Orobanche*. The adults lay eggs on the young *Orobanche* shoots and the larvae mine or tunnel through the stem and unripe seed capsules. As a result, *Orobanche* seed production is reduced to a great extent. However, several predators/ parasites/ parasitoids exist for *Phytomyza orobanche*, which limit its utilization as a potential bio-control agent for *Orobanche*. The Broomrape fly (*Phytomyza orobanchia*) is a widely occurring insect-pest of *Orobanche* sp. in Near East and North Africa (NENA) countries and natural reduction of *Orobanche* seed production of 11-79% has been reported from several NENA countries (Klein and Kroschel, 2002; Kroschel and Klein, 2004; Abang et al. 2007). Fungi: Almost 47 fungi species are isolated from the species of *Orobanche*, but a few proved effective against *Orobanche* under field conditions. One such fungus is *Fusarium oxysporum* f. sp. *orthoceras* (Appel and Wollenw.) Bilai from which “product F” was developed in the then USSR. It is mass reared on a medium of barley seeds and wheat straw and incorporated into the soil. It can cause massive damage to *Orobanche*. Sharma et al. (2011) reported that *Fusarium solani* infection on *Orobanche* increased the number of dead spikes of broom rape. Another important fungus is *Fusarium arthrosporioides*. Recently, in a study conducted in Iran on branched broomrape, *Talaromyces trachyspermus* has been identified as a potential biocontrol agent in branched broomrape. This was an isolate recovered from broomrape plants with high level of pathenogenicity to broomrape and further inoculation showed significant reduction in number of tubercles and increased rot symptoms in stalk. This could, hence, be an effective antagonist for broomrape biocontrol (Hemmati and Gholizadeh, 2019). Bacteria: *Pseudomonas aeruginosa*, *P. fluorescens*, *Bacillus atrophaeus*, *B. subtilis* are promising biocontrol agents targeting the growth of broomrape radicles (Barghouthi and Salman, 2010; Fernández-Aparicio et al. 2016).

Chemical control measures in Orobanche sp

Chemical weed control using herbicides has provided effective and cost-efficient weed control, thereby increased crop productivity significantly, although the bio-efficacy of herbicides varied across the locations (Das, 2001). It includes the following measures. Soil fumigation: Soil fumigation with dazomet (DMTT) granules at 300-350 kg/ha about 30-40 days before transplanting of tobacco is found effective. Similarly, metham (Vapum®) at 2000 l/ha (product) with narrow spacing of drippers is quite effective against *Orobanche* (Egyptian broomrape). Methyl bromide has been recognized as an effective soil fumigant (Braga et al. 2001) and is used to control localized populations of *Phelipanche ramosa* before planting tomato (Rathore et al. 2014). Also Kleifeld (2005) observed the effectiveness of methyl bromide applications for broomrape control; but the use of methyl bromide has been banned by World Health Organisation (WHO) and agricultural authorities due to its negative environmental effects (Punia, 2014). Application of Glyphosate*:* Foliar application of glyphosate twice, 25 g/ha at 30 DAS followed by 50 g/ha at 55 DAS would be very helpful in reducing *Orobanche* infestation by reducing the further increase in weed seed bank without yield reduction in mustard (Sheoran et al. 2014). Glyphosate can have directed use in a few crops, for example, faba bean, if applied at low dose (0.2-0.5 kg/ha). Its directed application in wider-row sown crops is more useful; Low dose of herbicides*:* Selective control of *Orobanche* can be achieved by applying some herbicides carefully at low rates. In mustard, 200 kg ha^{-1} neem cake + 0.5 kg ha^{-1} pendimethalin as pre-emergence, the use of neem or castor cake (400 kg ha^{-1} in furrows at sowing) + the direct application of glyphosate (50 g ha^{-1}) + 1% ammonium sulfate at 60 DAS appeared to be good for lowering the emergence of *Orobanche*, besides providing higher yields (Rathore et al. 2014). Application of 200 kg ha^{-1} neem cake and 2 kg ha^{-1} copper sulphate at sowing as separate treatments showed 34% and 41% reduction in *Orobanche* density in mustard in Rajasthan (Jat and Meena, 2018). Chinnusamy (2012) reported that drenching of plant holes with copper sulphate (5%) can reduce *Orobanche* infestation by 37% and increase dry leaf yield by 28% in tobacco. He also suggested application of neem cake at 150 to 200 kg/ha in rows at planting for lowering the density of this parasitic weed. He opined that in tobacco, plant hole application of neem cake at 200 kg/ha can lower the *Orobanche* shoots by 62% and increase dry leaf yield of tobacco by 51%. Pre-emergence control with chemicals*:* Oxyfluorfen at 200-250 g/ha as pre-emergence controls broad-spectrum of weeds along with *Orobanche* in mustard. Oxyfluorfen is selective to mustard and rapeseed. However, with regard to the control of *Orobanche* only, selective pre-emergence herbicide may not remain effective since *Orobanche* will germinate once mustard seedlings have developed some root system, but, by that time a sufficient time will elapse to reduce the effect of herbicide applied long back as pre-emergence. Therefore, oxyfluorfen, if applied as post-emergence at 200-250 g/ha in 400-500 litres of water at 30-35 days after sowing of mustard would be more effective.

Table 2: Chemical management of *Orobanche* sp. in field crops

SN	Herbicide	Crop	Time of application	Dose (kg/ ha)	Reference
1.	Glyphosate	Mustard	Directed application	0.025 kg/ha at 30 DAS *fb* 0.05 kg/ha at 55 DAS	Sheoran et al. (2014)
2.	Rimsulfuron	Potato	Foliar application (3 splits: 1st sprayed 2 weeks after crop emergence and re-applied at 2-week intervals	12.5 or 25.0 g/ha	Goldwasser et al. (2001)
3.	Sulfosulfuron	Tomato	Pre-emergence	75 g/ha	Dinesha et al. (2012)
4.	Neem cake + Pendimethalin	Mustard	Pre-emergence	200 kg ha^{-1} neem cake + 0.5 kg ha^{-1} pendimethalin	Rathore et al. (2014)
5.	Imazethapyr	Faba bean	Pre-emergence	75-100 g/ha	Garcia-Torres (1998)
6.	Imazethapyr	Garden pea and field pea	Post-emergence (1 month after planting and an additional application 2 weeks later)	20 g/ha	Punia (2014)
7.	Imazapic	Parsely	Post-emergence (5-7 leaf stage before 1st cuting and on new growth after each cutting)	2.5-5.0 g/ha	Goldwasser et al. (2003)
8.	Oxyfluorfen	-	Both pre- and post-emergence (30-35 DAS)	125-175 g/ha	Das (2008)
9.	Linuron	-	Pre-plant incorporation (more selective) and Post-emergence (30 DAS)	0.5 kg/ha, 1 kg/ha	Das (2008)

Dinesha et al. (2012) observed that pre-emergence application of sulfosulfuron at 75 g/ha controlled *Orobanche* effectively in tomato grown under irrigated conditions. Linuron at 0.5 kg/ha at 30 DAS caused complete control of *Orobanche*, but simultaneously posed severe phytotoxicity to mustard (Kumar, 2002). Therefore, pre-plant incorporation of linuron into the soil may be advocated, which could render selective control of *Orobanche* in tobacco and brinjal. Crenate broomrape was controlled in faba bean with imazethapyr at rates of 75 to 100 g ha^{-1} when applied before broomrape emergence (Eizenberg et al. 2012). Punia (2014) found split application with various imidazolinone herbicides on potato, sunflower and parsley foliage selectively controlled *Phelipanche ramosa*, *Orobanche cumana*, and *Orobanche crenata*, respectively. MH-T at 1.5 % spray on established *Orobanche* shoots as post-emergence also acts as effective control agent. 2,4-D, dinoseb, TCA have also been found effective against *Orobanche* in different crops; Post-emergence application of kerosene is also effective, but highly non-selective.

Bio-technological approach for *Orobanche* management

The bio-technological approach should be targeted towards developing host plant's resistance. It is usually bi-directional and can be achieved by two ways: i) developing host plants resistance against *Orobanche*; and ii) developing host plant's resistance to recommended selective herbicides. Enhancement of host plant's resistance by way of developing resistant varieties is one of the best methods of controlling *Orobanche*. Therefore, crop breeding and biotechnological researches for fostering *Orobanche* resistance in host crops should be more prioritized. Faba bean variety F-402, and pepper variety Maor and Odem are resistant to *Orobanche*. There are several herbicide-tolerant crop varieties developed in the world on which the respective herbicide can be used to control weeds including parasitic *Orobanche*. Several such crop varieties are chlorsulfuron-resistant tobacco, glyphosate-resistant rapeseed, asulam-resistant tobacco, glyphosate resistant tomato, asulam-resistant potato varieties. Punia (2014) reported effective control of broomrape was achieved when glyphosate application was done in oilseed rape having modified 5-enolpyruvyl-shikimate-3-phosphate synthase (EPSP synthase) enzyme and with asulam resistant tobacco plants having modified dihydropteroate synthase (methyl carbamate). Similarly Aviv et al. (2002) introduced a mutant AALS gene into carrot, which provided excellent control of broomrape by imazapyr (an imidazolinone ALS inhibitor).

Integrated Orobanche management

Several feasible methods/options can be integrated to form a workable integrated weed management (IWM) module including *Orobanche* or certain problematic perennial weeds (Kumar et al. 2012) in a specific area or crop for a long-term basis.

Biological control can be adopted on the basis of whole cropped and non-cropped area to manage *Orobanche* occurring on crop and wild hosts. *Orobanche*-resistant variety, if available should be adopted invariably in every situation or crop.

i) Soil solarization + optimum/ higher nitrogen fertilization + selective and effective pre-emergence herbicide + post-emergence herbicide or hand weeding/interculture at the later stages.

ii) Soil solarization or one or a few trap crop (s) or crop rotation with rice where feasible or prolonged flooding if possible with high temperature (during summer) + optimum/ higher nitrogen fertilization + selective and effective pre-emergence herbicide + hand weeding/ interculture at the later stages.

iii) Crop rotation with non-host crops like wheat, barley, chickpea, late sowing (25 October-10 November) of mustard supplemented with higher seed rate, use of organic manures in combination with increased N dose in fertilizer, two sprays of glyphosate at 25g/ha at 30 DAS and 50 g/ha at 55 DAS ensuring there is no moisture stress at the time of spray (Punia, 2014).

Conclusion

Orobanche spp cause severe problems in a large number of field crops worldwide leading to high crop losses. Its biological nature makes its control extremely ardous and expensive. A handful of weed control options are available now-a-days. They, however, individually are not a fool-proof strategy with having usefulnesses as well as limitations. Therefore, suitable options such as preventive, cultural, physical, biological/biotechnological and chemical as applicable should be integrated in a compatible and mutually exclusive manner to exhaust parasitic weed seed bank and achieve higher crop yields through improved weed management.

Conflicts of Interest

Authors declare no conflict of interest.

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