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Recent research progress in combating root parasitic weeds

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ABSTRACT
The obligate root parasitic Orobanchaceae plants Striga, Orobanche and Phelipanche spp. parasitize economically important crops, vegetables and oil plants. They are the most devastating agricultural weed pests worldwide. Based on an analysis of the climatic requirements of these parasites, very large areas of new territory are at risk of invasion if care is not taken. Recent research in combating root parasitic weeds was reviewed based on scientific papers reported from 2010 and onwards. The countermeasures fell into eight kinds: resistant varieties, tolerant varieties, microbiological approach, cultural practices, chemical controls, host-induced gene silencing, integrated management and dissemination of technologies including the current situation survey. The development of practical, feasible and economical control technologies against root parasitic weeds would be expected by advancing and combining the countermeasures.

Introduction
About 4000 flowering plant species have adapted to parasitize other plants [1]. Parasitic plants form specialized organs called haustoria that attach to hosts’ organs enabling them to benefit from the hosts’ water and nutrition, which severely damages the hosts’ growth and yield. Parasitic plants fall into two categories, root or stem parasitic weeds, according to the host organs to which they attach. Among root parasitic plants, the obligate root parasitic Orobanchaceae plants witchweed (Striga spp.) and broomrape (Orobanche and Phelipanche spp.) parasitize economically important crops, vegetables and oil plants. They are the most devastating agricultural weed pests worldwide [2].

The most important parasitic Striga spp. are the purple witchweed (S. hermonthica) and the Asiatic witchweed (S. asiatica). They are distributed throughout sub-Saharan Africa, India and Southeast Asia where they primarily affect cereal grass crops such as maize (Zea mays), sorghum (Sorghum bicolor), rice (Oryza sativa) and millet (Pennisetum spp.). Another important species, cowpea witchweed (S. gesnerioides), primarily attacks leguminous crops such as the cowpea (Vigna unguiculata) in West Africa. Crop losses by these Striga spp. can be up to 100% [3] and they have become the greatest biological constraint to food production in endemic areas [4,5].

The problematic weeds Orobanche and Phelipanche spp. are centred in the Mediterranean and Western Asia, but they are widely distributed throughout many countries all over the world [3]. Seven species, crenate broomrape (O. crenata), sunflower broomrape (O. cumana), nodding broomrape (O. cernua), fetid broomrape (O. foetida), small broomrape (O. minor), branched broomrape (P. ramosa) and Egyptian broomrape (P. aegyptiaca) are economically important [2]. Parker [3] determined that the main hosts are the Leguminosae, Apiaceae and Asteraceae for O. crenata, the sunflower (Helianthus annuus) for O. cumana, Solanaceae for O. cernua, Leguminosae for O. foetida, clover (Trifolium spp.) and alfalfa (Medicago sativa) for O. minor, and many families, including the Solanaceae and Brassicaceae, for P. ramosa and P. aegyptiaca.

The life cycle of Striga, Orobanche and Phelipanche spp. is strongly cued to that of its host. In nature, the seeds need a conditioning period of 2–14 days in a warm moist environment and subsequent exposure to a germination stimulant, such as strigolactone (SL), that is exuded by the host and some non-host plant roots. Subsequent to germination, which occurs in close proximity to the host roots, a haustorium is formed based on the perception of a second host-derived chemical signal. The haustorium attaches, penetrates the host root and establishes a connection with the host’s vascular bundles. Following the establishment of a connection with the host, the parasite remains subterranean and is fully dependent on its host for a certain period of time. After emergence, the absence or presence of functional
chloroplasts further defines the parasites as being either hemi-parasitic (Striga spp.) or holoparasitic (Orobanche and Phelipanche spp.), respectively. Each parasitic plant produces tens of thousands of seeds, which remain viable in the soil for 10 years or more.

It is estimated that 50 million ha in Africa are affected by Striga spp. [6] and 16 million ha in the Mediterranean region and Western Asia are affected by Orobanche and Phelipanche spp. [2]. Based on an analysis of the climatic requirements of Striga, Orobanche and Phelipanche spp., very large areas of new territory are at risk of invasion if special measures are not undertaken to limit the introduction of seeds and to educate farmers and others to be alert for signs of a new infestation [2,7,8]. In this review, we focus on recent research progress in combating root parasitic weeds, based on scientific papers that were reported during and after 2010.

Resistant varieties

Sorghum

At least four mechanisms were indicated in sorghum as potential resistance mechanisms against S. hermonthica using an extended agar gel assay, which allowed researchers to observe the parasites’ development in the rhizosphere of its host: (1) low production of germination stimulant, (2) secretion of germination inhibitor, (3) low production of the signals required for haustoria initiation and (4) hypersensitive response (HR) [9]. Two sorghum lines, CK32 and KP33, that exhibit a strong HR to S. hermonthica were used to elucidate the inheritance of the resistance mechanism. The results of the segregation suggest that HR in sorghum is conditioned by two nuclear genes with a dominant gene action [10]. As for the mechanisms ascribed to low production of the germination stimulant, there were varietal differences in SL exudation from roots, both quantitatively and qualitatively [11]. Sorghum varieties with a high 5-deoxystrigol (5-DS) level in root exudates had a higher S. hermonthica infection in the field, while those with a high orobanchol level had lower infection levels [12]. The functional loss of a gene at the LOW GERMINATION STIMULANT 1 (LGS1) locus resulted in a change of the dominant SL from 5-DS, a highly active S. hermonthica germination stimulant, to orobanchol, an SL that is less active to S. hermonthica [13]. Microsatellite markers linked to the low germination stimulant gene (lgs) for S. hermonthica were identified in sorghum and were supposed to be useful in breeding S. hermonthica-resistant sorghum varieties [14]. In breeding projects in Sudan and Eritrea, S. hermonthica resistance of sorghum was successfully improved by marker-assisted selection [15,16]. Resistance to S. hermonthica in wild sorghum accessions was reported as novel sources for sorghum breeding, in which the resistance was ascribed to incompatibility [17].

Rice

An incompatibility between some interspecific upland NERICA for Africa (NERICA) cultivars and S. hermonthica and between some NERICA cultivars and S. asiatica was found under laboratory conditions [18]. Activity to induce germination of S. hermonthica seeds and the level of SL production were studied in NERICA cultivars in laboratory and pot experiments and there were significant differences among the cultivars in these parameters [19]. The resistance level of NERICA cultivars screened under controlled environment [18,19] was in good accordance with that under field conditions [20], although they were not always exact. Furthermore, Rodenburg et al. [21] evaluated NERICA and other rice cultivars under field conditions in three regions of Africa and found that 11 and 8 out of 19 rice cultivars were resistant to S. hermonthica and S. asiatica, respectively. Under field conditions in Western Kenya, two cultivars, NERICA1 and NERICA10, were resistant and a cultivar NERICA4 was susceptible to S. hermonthica [22]. An upland rice variety, Umgar, which was released for commercial production in Sudan, showed several resistance mechanisms controlled by a low induction of germination and incompatibility in a series of laboratory, pot and field experiments [23]. The gene, WRKY45, modulates a cross talk in the resistance of rice against S. hermonthica by positively regulating both salicylic acid (SA) and jasmonic acid (JA) pathways [24].

Pearl millet (Pennisetum glaucum)

Kountche et al. [25] evaluated the response of a diversified pearl millet gene pool to five cycles of recurrent selection targeting S. hermonthica resistance and verified that the recurrent selection is effective for enhancing S. hermonthica resistance in the crop. A genetic map consisting of single nucleotide polymorphism (SNP) markers was constructed using a genotyping-by-sequencing approach and an F2 population was derived from a cross between S. hermonthica-resistant wild millet and S. hermonthica susceptible cultivated millet. The employment of such a map will be useful for the identification of genomic regions associated with S. hermonthica resistance and other important agronomic traits [26].

Maize

Although breeding maize varieties for S. hermonthica resistance was less successful until recent years [27],
massive development has been achieved mainly by the International Institute of Tropical Agriculture, Nigeria. A broad range of genetic diversity among maize varieties with *S. hermonthica* resistance was detected, indicating that a genetic reservoir of resistance can be exploited in breeding [28]. In fact, several *S. hermonthica*-resistant varieties with traits of extra-early maturing [29], early maturing [30] or high quality grains [31, 32] were developed for practical uses in Africa. In particular, maize varieties concurrently containing *S. hermonthica* resistance, drought tolerance, low soil N tolerance and a high yield ability [33–36] are expected to give acceptable performances at several growth conditions. In Nigeria, the largest seed company in the country participated in the selection of *S. hermonthica*-resistant varieties [37]. Maize varieties possessing incompatibility to *S. hermonthica* were recently identified [38]. In addition, new *S. hermonthica*-resistant maize varieties based on a low induction of germination were selected from 420 maize landraces, populations and elite inbred lines, although several maize landraces that are popular among smallholder farmers in Western Kenya had higher *S. hermonthica* resistance than the improved varieties [39]. Hybrid maize varieties with *S. hermonthica* resistance have also been recently developed [40, 41]. Heterotic grouping among 378 hybrids derived from diallel crosses of 28 early inbreds were evaluated in *S. hermonthica*-infested and *S. hermonthica*-free environments using SSR markers, to utilize the information in a maize hybrid breeding programme [42]. Very recently, the genetic diversity of tropical maize inbred lines combining resistance to *S. hermonthica* with drought tolerance was exhibited using SNP markers [43]. The effectiveness of marker-assisted recurrent selection to improve *S. hermonthica* resistance together with drought tolerance in maize breeding was demonstrated [44]. Hairy roots of transgenic ‘composite’ maize resulting from *Agrobacterium rhizogenes* transformation were shown to be infected by *S. hermonthica*, and this rapid, high throughput transformation technique will advance our understanding of gene function in parasitic plant–maize interactions [45].

**Cowpea**

*S. gesnerioides* exhibits a clear race structure; at least seven races of this parasite have been identified based on genetic diversity analysis and on their differential reaction to a panel of cowpea cultivars, suggesting a gene-for-gene interaction in the host–parasite association [46, 47]. The cowpea cultivar B301 is considered resistant to all *S. gesnerioides* races identified in West Africa, except race SG4z from Zakpota, Benin [48]. In the roots of B301, a distinct difference in global gene expression was found between compatible (susceptible) and incompatible (resistant) interactions with *S. gesnerioides* races SG4z and SG3, respectively [49]. Three well-characterized molecular markers (SSR1, C42-2B and 61RM2) for race-specific resistance to *S. gesnerioides* in B301 were used to analyse the genetic diversity of 81 cowpea accessions in Ethiopia, and only two accessions carried the SSR1 resistance allele. This wide diversity within cowpea accessions could contribute to the genetic improvement of cowpea germplasm for *S. gesnerioides* resistance [48]. Rapid DNA collection using FTA® cards (Whatman®) could provide a potential to put the marker-assisted selection of *S. gesnerioides*-resistant cowpea accessions on a fast track and increase the efficiency of breeding activities [50]. Two new cowpea genotypes, IT97K-499-35 and IT98K-205-8, had *S. gesnerioides* (race SG3) resistance comparable to B301, and their resistance was stable even under tremendously severe conditions of high *S. gesnerioides* infestation, low soil fertility and drought [51]. Eleven cowpea genotypes including IT98K-205-8 conferred resistance to several *S. gesnerioides* races [52]. The *S. gesnerioides* resistance is controlled by a single dominant gene (*Rgs*5) in IT98K-205-8 and two duplicate dominant genes (*Rgs*5a and *Rgs*5b) in another resistant accession, IT99K-573-1–1 [53]. An optimized protocol for the rapid generation of transformed hairy roots of ‘composite’ cowpeas using *A. rhizogenes* was described to study gene expression in resistance or susceptibility responses to *S. gesnerioides* [54].

**Sunflower**

Vrânceanu et al. [55] used a set of sunflower genotypes and identified that each of them carries one single major gene of resistance (*Or1* to *Or5*) and that these genes control races A to E of *O. cumana*, respectively, conferring resistance to previously described races (termed cumulative resistance). Sunflower varieties with resistance against race A to E of *O. cumana* have been reported. For example, one commercial sunflower in Argentina (cultivar M15) showed complete resistance to *O. cumana* race E [56]. However, it has been pointed out that the majority of the existing resistant genes have become insufficient due to the emergence of race F and higher [57]. Race E avirulence and race F virulence on a sunflower line are allelic and controlled by a single locus [58]. To attain sunflower varieties resistant to *O. cumana* races higher than F, the introduction of resistance genes from wild sunflower species to cultivated sunflowers has been studied [57, 59–63]. An inbred line, AB-VL-8, which originated from a population developed from interspecific hybridization with the rough sunflower (*Helianthus*...
**Faba bean (Vicia faba)**

Damage caused by *O. crenata*, *O. foetida* and *P. aegyptiaca* is important in faba bean cultivation throughout the Mediterranean and Near East [68]. A number of faba bean cultivars with resistance to *O. crenata* have been released, all of which use an Egyptian line Giza402 as the major donor of resistance [68,69]. Until recently, resistance mechanisms identified in the faba bean against *O. crenata* were ascribed to inhibition of radicle penetration and tubercle development [68]. However, a resistance mechanism in terms of low induction of germination has been found in faba bean cultivars, including Giza402 against *O. crenata*, *O. foetida* and *P. aegyptiaca* [68–73]. Resistance of several faba bean varieties against more than two *Orobanche/Phelipanche* spp. was confirmed even under field conditions [68,72,74–77]. Seven QTLs for *O. crenata* resistance and three QTLs for *O. foetida* resistance were identified using the faba bean. Co-localization of QTLs for *O. crenata* and *O. foetida* resistance in chromosome V confirms a common resistance against both parasites [75].

**Pea (Pisum sativum)**

Recently, a highly *O. crenata*-resistant pea line, named ROR12, was identified [86,87]. The resistance mechanism might involve the low induction of germination due to reduced secretion of SLs. The reduction of SL did not affect the yield of ROR12 [86,87]. The resistance of ROR12 is controlled by one or a few major genes localized on the pea linkage group 3 [86]. QTLs associated with *O. crenata* resistance were identified using recombinant inbred lines derived from a cross between a wild pea, *P. sativum* spp. *syracum* accession P665, and a susceptible pea variety, *P. sativum* spp. *sativum* cv. Messire [88].

**Chickpea (Cicer arietinum)**

The resistance of several chickpea genotypes to *O. foetida* has been investigated and three genotypes, FLIP 98–22C, Nayer and Beja 1, show partial resistance. Their resistance was ascribed to incompatibility [89]. Among 30 radiation-mutagenized chickpea mutants, five shared a strong *O. foetida* resistance based on a low induction of germination and incompatibility. When infested by *O. foetida*, most of the resistant mutants shared an enhanced level of soluble phenolic content, PAL activity and guaiacol peroxidase and polyphenol oxidase activities, in addition to glutathione and ascorbate peroxidase genes expression in the roots [90].

**Tobacco (Nicotiana tabacum)**

Among 89 tobacco genotypes, two ones, TB 22 and Kramograd NHH 659, did not show any susceptibility to *P. aegyptiaca* in pot experiments. Five SSR loci from linkage
groups 2, 10, 11 and 18 of a tobacco reference map were identified as DNA markers linked to gene(s) controlling *P. aegyptiaca* resistance in tobacco [91].

**Oilseed rape (Brassica napus)**

Gauthier et al. [92] characterized resistance to *P. ramosa* in oilseed rape. Three cultivars, ‘Darmor’, ‘Campo’ and ‘Shakira’, had resistance based on a low induction of germination, and the resistance of five cultivars, ‘Darmor’, ‘Campo’, ‘Adrianna’, ‘Expert’ and ‘Shakira’, was ascribed to incompatibility. In particular, infection of *P. ramosa* on the cultivar ‘Darmor’ remained significantly low compared to the other genotypes [92].

**Sesame (Sesamum indicum)**

Five sesame genotypes with an interesting trait were identified. *P. aegyptiaca* formed tubercles on their roots but no parasite shoots emerged [93]. Such sesame genotypes could be used as both trap crops and as breeding sources for the development of resistant genotypes [93].

**Grass pea (Lathyrus sativus)**

Promising sources of *O. crenata* resistance have been identified in wild peas (*Lathyrus cicera*) whose resistance was ascribed to a low induction of germination, incompatibility and escape from the parasite due to precocity or small root biomass [94]. Studies on the responses to *O. crenata* of 52 grass pea accessions under field conditions suggested that early maturing accessions and very late maturing accessions were less infected [95]. In addition, nine accessions, which were selected through a calculation of the deviations from the polynomial nonlinear regression between days to flowering of the host and the number of emerged parasites, would have true genetic resistance that was not dependent on the short and long growth length [95].

**Tolerant varieties**

Tolerance is used to describe the ability of the host plant to withstand the adverse effects caused by the attached parasitic weeds, regardless of their number [96]. Researches on tolerant varieties have not progressed compared to those of resistant varieties. However, tolerance will act as a safety net to prevent a sudden and unforeseen collapse in basic food supply in situations where resistance is overcome by root parasitic weeds [97]. Different tolerance criteria have been suggested, ranging from host plant damage scores to high yield, yield loss or relative yield loss under a *Striga* infestation. However, these criteria fail to distinguish the effects of tolerance and resistance on yield [98]. The relationship between the biomass of *Striga*-infected rice plants compared to uninfected rice plants and the dry weight (DW) of *Striga* attached to the rice roots identified several tolerant varieties [20]. A measurement of the photosynthesis rate at 30 days after sowing was a good indicator of *S. asiatica* tolerance for rice genotypes [21]. Three local landraces of sorghum in Sudan attained a satisfactory grain yield and crop biomass in spite of an *S. hermonthica* infection in field experiments at two locations. They may have tolerance to infection by the parasite [12]. Results from field experiments indicate that the grass pea is a less tolerant species to *O. crenata* parasitism compared to the faba bean and pea [99]. Identification of QTLs for tolerance would facilitate the systematic screening of a large group of crop genotypes and enable researchers to include this trait in cultivars with high levels of resistance [97].

**Microbiological approach**

**Fusarium spp.**

The fungal isolates reported to be pathogenic to parasitic weeds are, for the most part, *Fusarium* spp. [1]. Incorporation of *Fusarium oxysporum* (isolate 34-F0) inoculum into sorghum planting hills decreased *S. hermonthica* emergence and increased sorghum biomass in a field in Burkina Faso [100]. Nzioki et al. [101] developed a simple method using toothpicks for fungal delivery and trained smallholder farmers in Kenya to produce the biocontrol agent. In more than 500 farmers’ fields in Kenya, incorporation of *F. oxysporum* f.sp. *strigae* inoculum into the soil resulted in an average of 40%–50% increased maize yield [101]. By contrast, no difference was observed in the plant growth parameters and yield between maize plants grown from seeds inoculated with *F. oxysporum* f.sp. *strigae* and ones without any inoculation in *S. hermonthica*-infested fields in Kenya [102]. Unveiling the conditions under which *Fusarium* spp. can successfully control *Striga* is awaited. Inoculation of *F. oxysporum* f.sp. *strigae* did not have a harmful effect on rhizosphere prokaryotes, indigenous total fungal community and specific arbuscular mycorrhizal fungal taxa [103–105]. Coating sorghum seeds with a biocontrol strain of *F. oxysporum* had no adverse effects on sorghum seed germination, emergence or growth [106,107]. Twelve promising sorghum lines were identified with farmer-preferred agronomic traits and *F. oxysporum* compatibility. Using these sorghum lines, the development of an *S. hermonthica* control method in sorghum through the integration of host resistance and
F. oxysporum inoculation is expected [107]. The identified mechanisms by which F. oxysporum f.sp. striage control S. hermonthica are (i) complete digestion of S. hermonthica seedlings inside the host and (ii) wilting and killing the emerged S. hermonthica plants by clogging their vessels with hyphae [108]. The incorporation of three variant strains of F. oxysporum f.sp. striage, each of which excrete tyrosine, leucine and/or methionine, decreased S. hermonthica emergence and increased maize yield in S. hermonthica-infested fields [101]. In addition, the absence of Fusarium toxin production by these variants and wild-type F. oxysporum f.sp. striage was verified [101]. Plants of O. cernua infected by F. oxysporum Schltdl. collected from other plants of the parasite, quickly darkened and died. Genetic studies on infected and uninfected O. cernua suggested that F. oxysporum (i) caused heavy reactive oxygen species damage, (ii) induced significant irreversible genotoxic effects on the DNA, (iii) disturbed protein metabolism and synthesis and (iv) triggered apoptosis in the parasite [109]. Two F. compactum isolates highly pathogenic to O. crenata and O. ramosa were identified [110].

Arbuscular mycorrhizal (AM) fungi and rhizobium

Mycorrhizal fungi offer two advantages as biocontrol agents: they are not pathogenic to any crop plant, and they provide important additional benefits such as improved water and mineral nutrition. Their use as biocontrol agents offers an attractive complementary approach to breeding strategies and other biocontrol methods [111]. Inoculation of maize cultivars with AM fungi reduced the incidence and biomass of S. hermonthica. The inoculation increased N and P contents in maize cultivars, irrespective of the parasite infection [112]. Production and exudation of SL were significantly reduced by AM fungi symbiosis in tomato and the germination-inducing activities of P. ramosa were significantly ($p < 0.01$) lower in tomato plants colonized by AM fungi than in non-colonized tomato plants [113]. When sunflower was inoculated simultaneously with O. cuman and AM fungi, a moderate level of protection against the parasite was observed. This protection did not only rely on a reduced production of germination stimulants. Mycorrhizal root exudates had a negative impact on the germination of O. cuman [111]. Root exudates from pea plants colonized by AM fungi had lower germination-inducing activities to O. crenata, O. foetida, O. minor and P. aegyptiaca than those from non-mycorrhizal plants [114].

Several Rhizobium strains have been known to decrease the damage caused by parasitic weeds. The mechanisms of induced resistance in the pea by Rhizobium leguminosarum against O. crenata involve an elevated induction of the phenylpropanoid pathway, conferring mechanical and chemical barriers against the invading parasite [115]. Two R. leguminosarum strains (Mateur and Bouslel.96) were selected as potential inoculants to protect faba beans against O. foetida and to promote the host’s growth in pot and hydroponic co-culture (rhizotron) experiments [116]. Even in a faba bean field, the antagonistic effects of the strain Mateur on O. foetida were confirmed [117]. Inoculation of chickpeas with Rhizobium strains significantly decreased O. crenata and O. foetida seed germination and number of tubercles [118,119]. The effects of Rhizobium sp. strain PchAZm on O. foetida attacking chickpea roots were accompanied by enhanced levels of defence-related enzymes, PAL and peroxidase, in the host [120]. In addition, increased phenolic levels were recorded in the roots of Rhizobium-inoculated chickpea in the presence of O. foetida [120].

Fernández-Aparicio et al. [121] compared infection by O. crenata among a wild type, two non-nodulating and non-mycorrhizal mutants, and a super-nodulated mutant of the pea and barrel medic (Medicago truncatula). In both hosts, the establishment of O. crenata parasitism increase on the non-nodulating and non-mycorrhizal mutants suggested that Orobanche infection was partly controlled by pathways for AM fungi and Rhizobium symbiosis in the hosts [121].

Other fungi and bacteria

Aspergillus alliaceus isolated from O. cernua in sunflower fields very quickly caused necrosis and then greatly diminished the number of attachments, tubercles and emergent shoots as well as the total shoot number of O. crenata in laboratory, pot and field experiments [122]. Among the plant growth-promoting rhizobacteria tested by Mounde et al. [123], Bacillus subtilis GBO3 and Burkholderia phytofirmans PsJN had considerable potential in both S. hermonthica suppression through preventing germination and growth promotion of sorghum. A culture filtrate of an actinomycete strain, Streptomyces enissoacaesilis, significantly reduced the germination of O. cuman seeds in germination tests in Petri dish and rhizotron assays [124]. In addition, reduction of O. cuman tubercle formation, increase in activity of a defence enzyme, polyphenol oxidase, in sunflower roots and improvement of beneficial microflora in the rhizosphere soil of host plants were observed in S. enissoacaesilis-infested pots [124]. An endophytic bacterium, Pseudomonas strain PheS10, originating from tomato roots, suppressed P. aegyptiaca seed germination and reduced the number of P. aegyptiaca on tomato roots [125].
These examples illustrate the potential of some fungal and bacterial isolates as promising biocontrol agents.

**Cultural practices**

**Trap crop and catch crop**

Germination activities of rhizosphere soil, rhizosphere soil extracts and plant extracts of soybean (Glycine max) and maize collected in pot and field experiments were evaluated, from the view point of using soybean and maize as trap crops for O. cumana in sunflower-producing areas. The results suggested that soybean and maize could induce O. cumana germination and that they could be used as trap crops to control the parasite [126,127]. Soybean cultivars with many root nodules may have a higher potential as trap crops to control O. cumana because the germination percentage of the parasite positively correlates with soybean nodule diameter and DW [127]. A compound from rye (Secale cereale) root exudates, ryecarbonitriline A, induced germination of O. cumana, suggesting that rye has potential as a trap crop in sunflower production because it is not a host of the parasite [128]. Among other compounds exuded by rye roots, ryecyanatine A promoted a rapid cessation of O. cumana, O. crenata and O. minor radicle growth and rye-carbonitriline B had the same activity against O. cumana radicles [128]. Rhizosphere soil of foxtail millet (Setaria italica) cultivars had a germination-inducing activity to O. cumana seeds and rotation of foxtail millet and sunflower reduced O. cumana infection on sunflower. These results suggest that using foxtail millet as a trap crop is an effective way to reduce the incidence of O. cumana. The high adaptability of foxtail millet to dry conditions in China where farmers are suffering large-scale O. cumana infestation is an advantage of this crop in controlling the parasite [129]. A reduction in the emergence and shoot DW of O. crenata in lentil (Lens culinaris) fields were observed by growing flax (Linum usitatissimum) as a trap crop and lentil as a catch crop two months before the main lentil sowing [130].

The effect of trap crops on the management of P. aegyptiaca in tomato cultivation was studied in pot experiments by using eight crops: Egyptian clover (Trifolium alexandrinum), sesame, mungbean (Vigna radiata), flax, brown Indian hemp (Hibiscus cannabinus), cotton (Gossypium hirsutum), pepper (Capsicum annum) and black-eyed pea (Vigna unguiculata). In particular, sesam and brown Indian hemp decreased the biomass of P. aegyptiaca and increased tomato yield and were found to be the best trap crops [131]. The pea is also a potential trap crop to control P. aegyptiaca and O. foetida because the crop was not parasitized by the parasites but induced their germination [132]. Lilies (Lilium spp.), which are popular ornamental and medicinal plants in China, were proposed as a candidate trap crop for P. aegyptiaca for the same reasons as those for pea and O. foetida [133].

Differences in the germination-inducing activity to O. minor among wheat (Triticum aestivum) varieties including those with differing ploidy levels were studied as wheat was reported to have potential as a trap crop for the parasite [134,135]. Varietal differences were found in the germination-inducing activity [134], and germination of O. minor increased gradually with increasing ploidy levels of wheat [135]. Root exudates collected from cotton grown hydroponically, rhizosphere soil of field-grown cotton and plant extracts from the cotton had a germination-inducing activity to O. minor [136]. Selection and breeding of varieties with a high germination-inducing activity to O. minor would be possible in wheat and cotton. The screening of more than 600 Chinese medicinal herb species for an investigation of their germination-inducing activities to O. cumana, O. minor and P. aegyptiaca indicated that the methanolic extracts of many Chinese herbal species effectively stimulate seed germination of the parasites [137].

An economic analysis of different S. hermonthica control options including soybean-maize rotation, in which soybean was expected to act as a trap crop, was conducted in Western Kenya. The rotation was highly profitable due to increases in maize yield and additional production of soybean, compared to maize mono-cropping [138].

**Intercropping and mixed cropping**

The development of push-pull technology has been reported. In this technology, Desmodium spp. are used as an intercrop due to their allelopathic effects on S. hermonthica. Isoschaftoside extracted from silverleaf desmodium (D. uncinatum) roots was identified as the main growth inhibitor of germinated S. hermonthica radicles [139]. The number of farmers who adopted the technology was reported as 50,000 in 2013 [140], 80,000 in 2015 [141] and 125,000 in 2016 [142] in East Africa. An economic analysis by De Groote et al. [138] showed that push-pull technology was most profitable but required a higher initial investment cost, compared with soybean-maize rotation, green manure crop (Crotalaria ochroleuca)-maize rotation and adoption of herbicide-resistant maize (IR-maize) varieties. They pointed out that the limitation of the technology was that Desmodium spp. and Napier grass (Pennisetum purpureum), which were planted as border crops to attract stem borers, were sensitive to drought and that this technology was only
recommended in areas with sufficient livestock and a demand for fodder to make money out of the *Desmodium* spp. and Napier grass pastures [138]. To expand the push-pull technology to areas where livestock is not a major component of the farming system, effects and economic benefits of intercropping maize with food legumes were compared with that with *Desmodium* spp. Although intercropping maize with food legumes was more profitable than a maize mono-crop, greenleaf desmodium (*D. intortum*) provided a more consistent and significant suppression of *S. hermonthica* and higher economic benefits than food legumes [143]. Furthermore, to expand the push-pull technology to drought-prone areas, climate-adapted push-pull technology using drought tolerant *Desmodium* spp. and Napier grass (or other grasses) as the intercrop and border crop, respectively, has been developed [141,142,144–147]. This improved technology is currently practised by more than 54,000 farmers in East Africa [142] and a higher percentage of women perceived the improved technology as very effective compared to men [146]. *D. uncinatum* and *D. intortum* were compared in their own biomass production and in their growth-promoting effects on maize. *D. intortum* consistently gave a higher fodder yield compared with *D. uncinatum*, but resulted in a somewhat lower maize grain yield [148]. Push-pull technology succeeded in controlling *S. hermonthica* in rice [149], finger millet (*Eleusine coracana*) [150] and sorghum [151] cultivation, as well as maize.

Intercropping food legumes (faba bean and pea) with Egyptian clover reduced *O. crenata* infection, irrespective of host food legumes [152]. From the viewpoint of controlling *Orobanche* and *Phelipanche* by intercropping or mixed cropping, attention has been paid to black oat (*Avena strigosa*) because it exudes avenaol, which has a high germination-inducing activity to *P. ramosa* seeds [153]. Mixed cropping of cowpea and sorghum may provide an easy and accessible means for controlling *S. gesnerioides*, as sorghum roots exude sorgolactone, sorgomol and 5-DS [11], which induce germination of *S. hermonthica* seeds but inhibit the germination of *S. gesnerioides* seeds [154]. The inhibiting activities of some SLs to *S. gesnerioides* germination are attributable to their stereostructures [154].

**Other cultural practices**

Many studies report a decrease in parasitic weeds infection with the application of N and P nutrients. Dramatic increases in SL production by N and P deficiency have been reported in red clover (*Trifolium pratense*), sorghum and tomato, inducing more germination of the parasitic weeds’ seeds [155]. This relationship was confirmed in associations of maize–*S. hermonthica* [155], rice–*S. hermonthica* [156], sorghum–*S. hermonthica* [157], tobacco–*O. cumana/O. crenata* [158] and faba bean–*O. foetida* [73]. Only P deficiency promoted SL exudation in alfalfa and tomato, and N as well as P deficiencies promoted it in Chinese milk vetch (*Astragalus sinicus*), marigold (*Tagetes patula*), lettuce (*Lactuca sativa*) and wheat [159]. These findings suggest that a fertilizer application could play a vital role in reducing germination stimulant production in host plants and hence, possibly, the infection of parasitic weeds. Micro-dosing of diammonium hydrogen phosphate fertilizer, which is commercially available and popular among farmers in Africa, was proposed as an efficient and cost-effective *S. hermonthica* control option because it reduced *S. hermonthica* damage in sorghum fields in Mali [157]. *Striga* infestation became heavy as soil K content increased in farmers’ fields in Tanzania and Nigeria [160,161]. The excess K treatment resulted in an increased germination-inducing activity of tobacco root exudates to *O. cumana* and *P. aegyptiaca* [158].

The effects of organic matter amendment on *S. hermonthica* control have been controversial [162]. High quality organic matter (low C:N ratio) incorporated in the soil significantly depressed *S. hermonthica* seed survival, emergence and biomass [162,163]. Ethylene induced *S. hermonthica* germination but the soil ethylene concentration was not affected by the quality of the applied organic matter, indicating that the effect of high quality organic matter on *S. hermonthica* control was irrelevant to ethylene in the soil [162]. Nutrient release, in particular N, through the decomposition of organic matter was proposed as the probable cause of the depressive effects on *S. hermonthica* [162,163].

Early planting of tomato in Turkey resulted in the lowest *P. aegyptiaca* emergence and the highest tomato yield [83]. Early sowing of sorghum in Nigeria increased *S. hermonthica* emergence and the optimal sowing date differed among sorghum varieties [164]. Investigation of the appropriate planting/sowing date under each target condition would be necessary to control parasitic weeds.

For high-value cash crop production, soil solarization and a biochar application would be options to control parasitic weeds. Soil solarization by covering soil with transparent plastic film was effective to control *P. ramosa* in tomato production under greenhouse conditions in Italy and Turkey [165–167]. The efficacy of this technique was improved when combined with supplementation of organic matter [166,167]. The efficacy also increased when repeated or long-term solarization was conducted [165,167]. In Israel, adding biochar to soil decreased *P. aegyptiaca* germination, leading to improved tomato growth. The major cause of the decrease in the
germination percentage was physical adsorption of the stimulant molecule by biochar [168]. Another approach, that of covering soil with maize straw (i.e. mulching), suppressed S. hermonthica in maize fields in Kenya, but the effect was much weaker than that of the intercropping of maize with D. uncinatum [140].

Chemical control

Suicidal germination

The suicidal germination approach was proposed as far back as 1976. This methodology involves the application of a germination stimulant to the soil in the absence of a host. The seeds of the parasite will germinate but soon die due to the lack of nutrients. However, field trials on the efficacy of artificial germination stimulants to induce suicidal germination of the parasitic weeds have not been conducted, probably because of the instability of the stimulants, particularly in alkaline soils, and lack of a proper formulation [1,169]. Kgosi et al. [170] evaluated the activities of five SL analogues in soil using S. hermonthica or S. asiatica seeds in packets which were put in pots with pH neutral soil, and then treated with aqueous solutions of the analogues. All of the compounds induced germination under these conditions and the best performing stimulant, which was derived from 1-tetralone, induced 98.0% germination for S. hermonthica seeds [170]. Furthermore, a formulated SL mimic, T-010, and a formulated SL analogue, Nijmegen-1, reduced the emergence of S. hermonthica in sorghum fields and P. ramosa in tobacco fields, respectively; thus, the technical feasibility of suicidal germination was proved [169,171]. It should be pointed out that both T-010 and Nijmegen-1 are hydrolysed faster than an SL analogue, GR24, which had been reported as an unstable compound in soil [169,172]. The feasibility of suicidal germination cannot be disesteemed because of an instability of artificial germination stimulants. The germination-inducing activity of T-010 in Petri dishes was lower than GR24, but T-010 induced significantly more seed germination than GR24 in soil, suggesting that mobility in soils is more important than intrinsic activity for a suicidal germination inducer [169]. Structure modification of artificial germination stimulants resulted in an improvement in the germination-inducing activity [173–176]. Although conditioning prior to applying artificial germination stimulants was a prerequisite for the success of a suicidal germination approach [169,171], Yao et al. [177] reported that conditioning was probably not the indispensable stage of P. aegyptiaca based on the finding that the transcript level of genes relating to SL signalling was not up-regulated by the conditioning treatment.

The identification of SL receptors in parasitic weeds unlocks the door for high-throughput chemical screens, similar to the success with Arabidopsis KAI2 receptor to identify additional parasite germination agonists [178,179]. Yoshimulactone Green, which activates SL signalling and illuminates signal perception by SL receptors, enabled access to SL receptors and observation of the regulatory dynamics of SL signal transduction in S. hermonthica [180]. Arabidopsis expressing ShHTL7, the most functionally sensitive SL receptor in S. hermonthica, could function to screen chemicals to induce germination of the parasite [181].

Studies on natural germination stimulants have progressed. Sesquiterpene lactones, dehydrocostus lactone, costunolide, tomentosin, 8-epidanethin and a non-sesquiterpene lactone, heliolactone, were isolated from sunflower root exudates as germination stimulants for O. cumana [182–184]. Three new polyphenols, named peapolyphenols A–C, isolated from pea root exudates were found to strongly stimulate seed germination of several Orobanche and Phelipanche spp. [185]. Soyasapogenol B, which specifically induced O. minor germination, and trans-22-dehydrocampesterol, which induced O. crenata, O. foetida, O. minor and P. aegyptiaca germination, were isolated from common vetch (Vicia sativa) root exudates [186]. From oilseed rape root exudates, 2-phenylethyl isothiocyanate was identified as a germination stimulant for P. ramosa [187]. Root exudates from black oat contained avenanol, which is a potent germination stimulant of P. ramosa seeds, but it exhibited only a weak activity to seeds of S. hermonthica and O. minor [153]. The structure of a major SL produced by M. truncatula was determined and named medicaol [188]. Medicaol has a seven-membered cycloheptadiene in the A ring instead of a typical six-membered cyclohexene [188]. Novel SLs, zealactones, were isolated from maize root exudates as a germination stimulant of S. hermonthica seeds [189]. The mechanism of host recognition by Orobanche and Phelipanche might have been specialized to different combinations of SLs and their concentrations present in each host root exudate [190]. The absolute configurations of enantiomerically pure SL analogue series were elucidated by X-ray analyses and CD spectra. It was confirmed that analogues bearing the R-configured butenolide moiety showed enhanced biological activity [191].

Herbicides

One potential option that may offer a practical means for small-scale farmers to control parasitic weeds is the use of a seed treatment with low doses of acetolactate synthase (ALS)-inhibiting herbicides (imidazolinone herbicides) such as imazamox, imazapic and imazapyr.
Imidazolinone resistance (IR) genes were incorporated into tropical maize lines that adapted to the growth conditions in Africa and the imazapyr-coated seeds of these IR maize lines planted under *S. hermonthica* infestation in Nigeria supported very few emerged parasites and sustained a limited yield loss [192,193]. In four countries of Eastern Africa, imazapyr-coated seeds of other IR maize varieties supported significantly fewer *Striga* emergence and showed more grain yield than commercial varieties without the herbicide coating [194]. In Israel, application of imazapic and imazapyr during tomato cultivation using an IR tomato mutant demonstrated high *P. aegyptiaca* control efficacy [195].

Glyphosate disrupts the biosynthesis of aromatic amino acids by inhibiting 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS). This glyphosate activity was confirmed in *P. aegyptiaca* using glyphosate-resistant tomatoes [196].

Dor et al. [197] showed that the main mechanism by which ALS-inhibiting herbicides and glyphosate control *P. aegyptiaca* is direct inhibition of the enzymes ALS and EPSPS, which are present and active in the parasite tissues. Around the same time, a secondary effect of glyphosate action, inhibition of the translocation of phloem-mobile solutes from the tomato to *P. aegyptiaca*, was indicated [198].

Adjustment of doses and timing of the herbicide application is another important topic. In a decision support system developed in Israel for the control of *P. aegyptiaca* in tomato fields, the timing of the herbicide application was based on a thermal time model that was developed to predict parasitism of *P. aegyptiaca* on tomatoes [199]. The model was also effective for predicting the entire parasitism dynamics, not only for predicting the first attachment, and could be used for precise temporal chemical management of *P. aegyptiaca* in carrot (*Daucus carota*) fields [200]. Three sequential foliar applications of glyphosate at 108 g/ha completely controlled *P. aegyptiaca* in carrot fields [201,202]. Moreover, applying glyphosate to carrot plants at high temperature injured them and reduced the *P. aegyptiaca* control efficacy [202]. The effects of temperature and water conditions on *O. crenata* seed germination and radicle growth were determined from the view point of developing a predictive infection model [203].

### SA- and JA-mediated plant defence responses

Induction of systemic acquired resistance in host plants to root parasitic weeds by a foliar application of SA and an SA analogue (benzothiadiazole [BTH]) was proposed. The induction was further evidenced using faba bean–*O. crenata* and faba bean–*O. foetida* systems [64,204]. A foliar application of BTH or JA on rice induced an increased resistance against *S. hermonthica*, indicating that BTH and JA induce systemic resistance against the parasite in rice [24]. Interestingly, transgenic SA-deficient (NahG) rice plants exhibited an enhanced resistance to *S. hermonthica*. However, a foliar application of BTH did not complement the loss of SA in NahG rice plants, suggesting that BTH and endogenous SA may have different effects on *S. hermonthica* resistance in rice [24]. Sunflower seeds pretreated with SA and then grown in pots containing *O. cumana* seeds showed an increased biomass via reducing the number and biomass of established *O. cumana*, suggesting that the treatment invokes a defence mechanism of the host against the parasite [205].

### SL biosynthesis inhibitors

SLs are biosynthesized through carotenoid cleavage, and possibilities to reduce SL production in rice roots by using carotenoid biosynthesis inhibitors have been studied. A low concentration of carotenoid inhibitors, fluorida, norflurazon, clomazone and amitrole significantly decreased SL production by rice roots with no effect on rice growth, suggesting an effective technology to control parasitic weeds [206]. Ito et al. [207] discovered that a triazole-type chemical, TIS13, is a lead chemical for SL biosynthesis inhibitors in rice, and a TIS13 treatment to rice seedlings reduced SL levels in both roots and root exudates with growth retardation of rice. The structure of TIS13 was modified to develop more potent and specific inhibitors. As a result, TIS108 was found to decrease SL levels in roots and root exudates without growth retardation of rice [207,208]. A gibberellin (GA) treatment in a nutrient solution for a rhizotron experiment reduced the infection of rice plants by *S. hermonthica* due to the novel plant hormone crosstalk in which the application of GA to rice plants reduced the level of SLs [209].

SLs act as endogenous hormones to inhibit shoot branching. The combination of SL-deficient host plants which tend to have many branches with an SL mimic, 4-Br debrananone, was proposed because the mimic had a low germination-inducing activity to *S. hermonthica* and a high shoot branching inhibiting activity [210].

### Decomposition of SL in soil

Hydrolysis of SLs by either borax or thiourea was verified in a laboratory and a novel concept for parasitic weed control by decomposing SLs in soil was proposed [172]. This concept was proved in experiments where borax and thiourea were applied to root zones of tomatoes growing in *O. crenata*-infested soil. Effective quenching of SLs could be achieved using borax and thiourea at an effective concentration of 1–5 mmol/L, which was well below the damaging range exerting phytotoxicity on
tomatoes [211]. These results demonstrate that the concept of timely SL decomposition in soil will be a feasible method for parasitic weed control.

Other chemical control agents
A galactosyl-sucrose trisaccharide, planteose, was found to be a required storage carbohydrate for the early stage of germination of *O. minor* through a metabolomics analysis of germinating seeds of the parasite. Nojirimycin bisulfite inhibited the germination of *O. minor* seeds by blocking the supply of glucose from planteose and sucrose, suggesting that a galactosidase inhibitor such as nojirimycin bisulfite is a lead chemical to develop an *O. minor*-specific herbicide [212]. A proteome analysis of the pea parasitized by *O. crenata* [213], a metabolome analysis of *P. aegyptiaca* at several growth stages [214] and a transcriptome analysis of several parasitic weeds [215] might lead to the identification of new targets for the specific control of parasitic weeds. Holbrook-Smith et al. [216] developed a high-throughput screen for compounds that antagonize SL signalling in the model plant *Arabidopsis thaliana*. One compound selected, soporidine, specifically inhibited the function of an SL receptor in *S. hermonthica* and then the parasite’s germination, suggesting that the small molecules that perturb SL signalling are useful for disrupting the lifecycle of *S. hermonthica* [216]. A foliar application of maleic hydrazide to tomato reduced *P. aegyptiaca* attachment on the host roots without any influence on tomato foliage or root DW. Maleic hydrazide was registered for use in Israel in 2013 with the specified protocol, and today it is widely used by most Israeli tomato growers for *P. aegyptiaca* control [217]. Amino acids, lysine, methionine and triptophan applied to red clover fields by irrigation interfered with *O. minor* early development and may have the potential to be integrated into biorational programmes of the parasite [218]. Efficacy of a soil fumigant, dzamet, which releases the toxic gas methyl isothiocyanate to control *P. mutelii* was confirmed under field conditions in Australia [219]. Although soil fumigation indiscriminately targets both beneficial and harmful biota [166], this method is an option to eradicate the seed bank of parasitic weeds.

Host-induced gene silencing
The concept of host-induced gene silencing is that the silencing constructs for essential parasite genes are transformed to host plants and suppress the parasite’s growth because of movement of the small interfering RNA from the host to the parasite, where the actual silencing takes place [220]. Recently, host-induced gene silencing has been used to silence genes encoding the acetyl-CoA carboxylase in yellowbeak owl’s-clover (*Triphysaria versicolor*), a facultative root parasitic plant, and the KNOTTED-like homeobox transcription factor, SHOOT MERISTEMLESS-like in dodder (*Cuscuta pentagona*), a shoot parasitic plant. This successfully reduced parasite viability, confirming the usefulness of this technique [220–222]. To identify putative candidate genes for host-induced gene silencing, high throughput screening protocols using a virus-induced gene silencing system in *S. hermonthica* are useful [223]. Host-induced gene silencing is one of the fields that utilizes results from The Parasitic Plant Genome Project [215].

Integrated management
The package involving the *S. hermonthica*-resistant sorghum variety, water harvesting through tied-ridge tillage and N fertilizer suppressed the parasite development and increased the host’s grain yield more efficiently than each component of the package in sorghum fields in Ethiopia. In particular, the resistant variety served as a central component in the package [224]. Reinhardt and Tesfamichael [151] studied how to integrate *S. asiatica* tolerant sorghum cultivars by intercropping *D. intortum* and using N fertilizer, and considered parasite control and host yield. They achieved 100% *S. asiatica* control and a dramatic increase in sorghum yield with 100 kg N/ha in a 1:1 sorghum–*D. intortum* intercropping [151]. The use of an *S. hermonthica*-resistant sorghum variety, biocontrol based on *Fusarium* inoculum and intercropping with cowpea had a synergistic effect in controlling the parasite [100]. In an association of tomato–*P. ramosa*, 12 agronomic, chemical, biological and biotechnological strategies for the control of the parasitic weed were evaluated as basic information for further integrated management. Based on the information, the integrated strategy composed of a biostimulant that contains humic substances, N or S fertilizers, compost activated with *F. oxysporum*, a soil fumigant and resistant tomato cultivars was designed. The strategy successfully mitigated the virulence of the attacks of *P. ramosa* [81]. Since it is generally believed that integrated management is the only way to cope with the parasitic weeds [1], further verification examples are needed to develop effective, economical and applicable management under each target condition.

Current situation survey and dissemination of technologies
Surveys of *S. hermonthica* infestation in Northern Cameroon over the period 1987–2005 assessed *S. hermonthica* dynamics and its control strategies [225]. The percentage of *S. hermonthica*-infested fields increased in the country
and \textit{S. hermonthica} incidence increased more in maize fields than in the already heavily infested sorghum fields, where it remains almost constant [225]. Rodenburg et al. [226] conducted the first multi-species (including \textit{S. asiatica} and \textit{S. hermonthica}), multi-country and single crop (rice) impact assessment of parasitic weeds in Africa, using a combination of data mining, spatial analysis and stochastic impact assessment. An estimated 1.34 million ha of rain-fed rice is infected with at least one species of parasitic weed in Africa with estimated economic losses inflicted by all parasitic weeds of roughly US$200 million, which increases by US$30 million annually [226]. In tobacco fields, the relationship between environmental variables, such as soil and bioclimatic factors, and the level of infestation with \textit{P. aegyptiaca} and \textit{P. ramosa} was identified on a massive scale in Greece to provide information for modelling the parasites’ infestation based on abiotic factors and to create a baseline for future monitoring of their distribution. Soil pH, total humidity index and organic matter content were the most decisive variables for the severity of \textit{P. aegyptiaca} and \textit{P. ramosa} infestation [227].

Farmers’ perceptions and the potential adoption of \textit{S. hermonthica} control measures were evaluated in Western Kenya. Although the level of \textit{S. hermonthica} infestation and damage was increasing in the farmers’ fields, the adoption of control options was limited because the farmers thought that the control options were too risky as there was no guarantee of a direct pay-off in increased crop yield [228]. Although parasitic weed infestation was associated with poor soil fertility, farmers did not use fertilizers due to various factors, ranging from fears of undesirable agronomic side effects to a lack of quality control of fertilizers [229]. A lack of coherent policies on parasitic weeds and lack of policy implementation were observed at higher organizational levels. Accordingly, extension systems could not provide farmers with advice [229]. In Kenya, a structure questionnaire evaluated gender-specific perceptions and the extent of adoption of a new technology, in this case, a climate-adapted push-pull technology. The results indicated that a slightly higher percentage of women perceived the technology as effective compared to men [146]. Farmers’ appreciation of \textit{S. hermonthica} control technologies changed from year to year and from village to village [230]. In Ethiopia, farmers preferred sorghum landraces to improved released varieties [231]. Adoption of improved \textit{S. hermonthica} control technologies by farmers was also limited due to a lack of information, fear of risks associated with the novel technologies, financial limitations, their preference for traditional control methods and lack of access to new variety seeds [231].

Conclusions

Several promising approaches for combating root parasitic weeds have been developed recently such as maize varieties possessing concurrent \textit{Striga} resistance with other stress tolerances in West Africa, a simple method using toothpicks for fungal delivery in soil for farmers in Kenya, push-pull technology widely adopted by farmers in East Africa and a decision support system for controlling \textit{P. aegyptiaca} in Israel. In addition, progress in other approaches would increase possible elements in integrated management, which is believed as the only way to cope with parasitic weeds due to the lack of a consistently effective, economical and applicable approach irrespective of conditions. Further researches are imperative because the number of resistant and/or tolerant varieties are not enough in many crops, the validation of many microbiological approaches and chemical controls is expected under practical conditions and adjustment of cultural control to the target conditions is inevitable. Moreover, it takes some time before new biotechnology-based approaches become utilized in the control of root parasitic weeds, and dissemination of technologies including the current situation survey is another important task. A deeper understanding of parasitic weeds, host plants, their growth environment and the social circumstances of people involved should lead to the development of appropriate approaches.

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