Chapter

Management of Branched Broomrape in Field Processing Tomato Crop

Francesco Lops, Laura Frabboni, Antonia Carlucci, Annalisa Tarantino, Maria Luisa Raimondo and Grazia Disciglio

Abstract

In recent years, there has been a considerable increase in land area used for tomato (*Lycopersicon esculentum* Mill.) in many countries around the world. The essential role is played by Italy at a worldwide level as the country with the third biggest production of tomatoes for processing. *Phelipanche ramosa* (L) Pomel, commonly known as branched broomrape, is a root holoparasitic weed for many crops, particularly for the processing tomato. Due to its physical and metabolic overlap with the crop, its underground parasitism, and hardly destructible seed bank, the control of this parasite in the field is difficult. Results of research studies, many of them on environmental-friendly methods such as preventive, agronomic, and biological carried out in southern Italy, are discussed and summarized. The results can constitute a relevant basis for further experimental studies.

Keywords: orobanche, *Phelipanche ramosa*, control methods, processing tomato crop, cultural practices

1. Introduction

Tomato (*Lycopersicon esculentum* Mill.) is the vegetable crop with the highest demand and the greatest economic value in the world. Tomato trade and production have particular importance in tropical, subtropical, and mild regions of the world, for both fresh and processing markets [1]. In recent years, there has been a considerable increase in the world land area used for tomato production. The essential role is played by Italy at a worldwide level as the country with the third biggest production of tomatoes for processing after the United States and China. The 2021 tomato processing campaign in Italy closed with a production of just over 6 million tons of processed product, up 17% compared with 2020. Italy's production is 13% of the world's and 53% of Europe [2].

In Italy, as in other areas of the world [3, 4], and especially in the Mediterranean basin, the tomato crop and other species (broccoli, fennel, parsley, celery, and chamomile) are undergoing increased attack of a holoparasitic plant with obligate

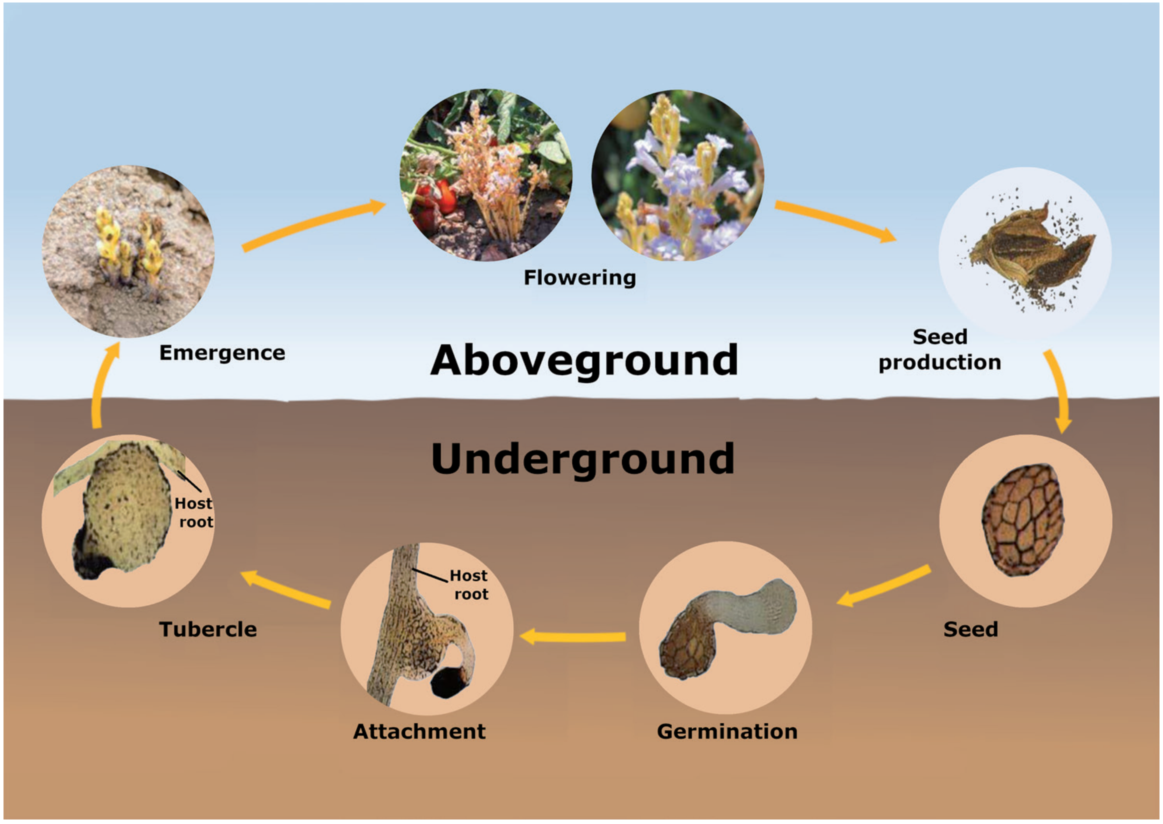

Figure 1.
A summarized life cycle of a branched broomrape (from Osipitan et al., 2021) [6].

root belonging to the *Orobanchaceae* family, the *Phelipanche ramosa* (L.) Pomel (syn. *Orobanche ramosa* L.), commonly known as the branched broomrape. Tomato is highly vulnerable also to similar species, as the *Phelipanche aegyptiaca* Pomel (syn. *O. aegypt*iaca) and *O. cernua* Loefl., which are known to cause damage and yield reductions in this crop [5]. The broomrape seeds only germinate in response to specific chemicals (strigolactones) released by the host plant, and the plant spends most of its life cycle underground (**Figure 1**) [7, 8].

Following germination, the seedlings attach to the host roots by the production haustoria that penetrate the host tissues until they reach the vascular system for uptake of water and nutrients, assimilate, and grow at the expense of the host plant's resources [5]. *P. ramosa* attacks tomato roots early in the growing season, within 14–28 days after transplanting (DAT), depending on the temperature conditions, and the shoot usually emerges within 35–56 DAT [9]. Once connected to a host plant, broomrape grows rapidly, forming a tubercle (a storage organ for nutrients and water extracted from the host) underground. Multiple shoots (up to about 20) develop from the tubercle and emerge above the soil surface, and then grow to stalks from 15 cm to 30 cm in height (**Figures 2** and **3**). Flowering begins within 3–7 days after a broomrape shoot emerges above the soil surface. A mature broomrape plant can release more than 500,000 seeds (from 0.2 to 0.4 mm), which can remain dormant and viable for many years (> 20) in soil [5]. The number of emerged shoots per surface unit, and/or number and dry weight of parasitic plants per host plant, can be used as indicator to monitor *Phelipanche infestation* [10].

The air and soil temperature are the main factors that influence the dynamic of host/parasite interaction and development. Moreover, the optimum temperature for maximum germination of *Orobanche* seeds decreases as the level of their water stress increased [11].

Figure 2.
Branched P. ramosa *plant (F. Lops).*

Figure 3.
P. ramosa *infestation in tomato (F. Lops).*

The presence of the parasite causes a significant reduction in the photosynthetic capacity of tomatoes, as shown by the higher SPAD chlorophyll indices detected on the leaves of infested tomato crop compared with the non-infected one (**Figure 4**).

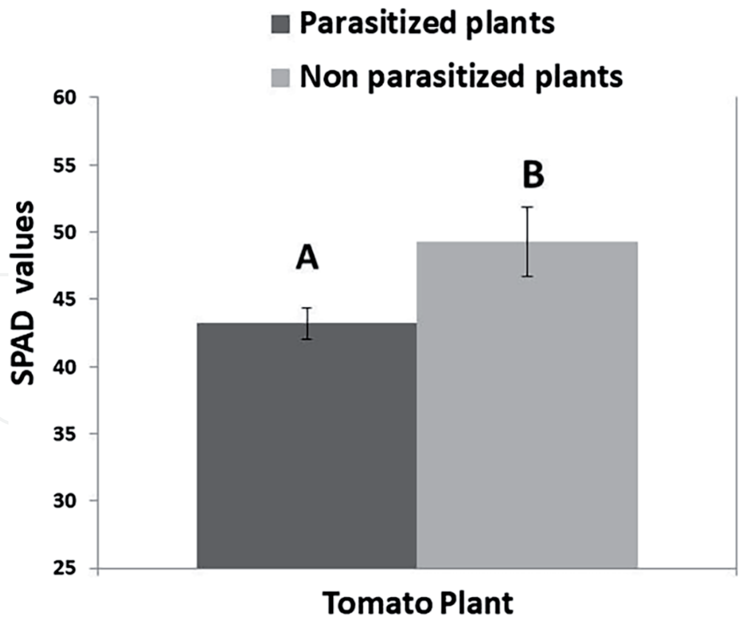

Figure 4.
Average SPAD values ± SD of parasitized and non-parasitized tomato plants, measured at 53 days after transplanting. Different letters indicate significant differences at P <0.05 according to Tukey's test [12].

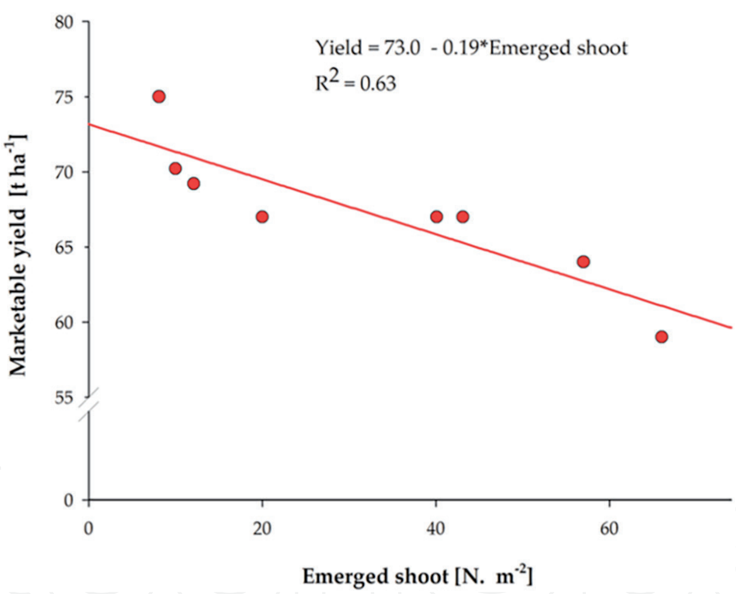

Figure 5.
Relationship between tomato marketable yield and number of emerged branch shoots of P. ramosa detected at the end of tomato cycle (harvesting time) [14].

This generates a loss of biomass of their aerial organs [13] and a significant decrease in crop yield (**Figure 5**), mesocarp thickness, fruit color, compactness, content of soluble solids, of ashes, and of ascorbic acid [15].

2. Management of *P. ramosa* in the field

Effective control of *P. ramosa* is difficult because, as already mentioned, most of its life cycle occurs below the soil surface. Thus, the effective management of this parasitic weed will require a long-term and an integrated approach. Measures to successfully contain the problems due to *P. ramosa* need to be targeted at: i) reduction of the existing *P. ramosa* seed bank in the soil; ii) prevention of further seed production; and iii) prevention of seed dissemination. These objectives are mutually dependent. Practices to control this parasite include several methods (preventive, chemical, agronomic, and biological), which help to avoid germination, infection, or strong reproduction of the weed [16, 17].

2.1 Prevention methods

Preventing the movement of parasitic weed from infested into un-infested areas or its spread in recently infested fields is a crucial component of control. Principal measures are to remove the *Orobanche* prior to flower opening; the quarantine for a period of at least 2 years, and in subsequent years only rotational crops may be cultivated (e.g., in California, these crops are those approved by the local agricultural commissioner); clean and disinfect all equipment used in a field with broomrape infestation [6, 17]. As for seed eradication on farm equipment, quaternary ammonium compounds have been found effective in *Phelipanche* and *Orobanche* spp. [18].

2.2 Chemical methods

Herbicides that currently are in use for parasitic weed broomrape control in various crops are sulfonylurea and imidazolinones. Sulfonylurea herbicides are absorbed through the host plant foliage and roots with rapid acropetal and basipetal translocation. Imidazolinone herbicides are absorbed and translocated through the host to the meristematic tissues. The most successful method to the parasite control in processing tomato is to apply sulfonylurea herbicides, on foliage and by injection through the drip irrigation system in preplanting, or post-emergence, or post-planting [19]. Soil herbigation (saturating the soil with sulfonylureas) effectively controls pre-attached stages of broomrapes [20], but this is hardly compatible with other agricultural cropping practices, as detrimental for many crop seedlings for several weeks or months. Applying sulfosulfuron to the soil three times, at 200, 400, and 600 growing degree days, followed by two applications of imazapic to the tomato foliage late in the season, effective Egyptian broomrape control has been achieved [21, 22]. In the conditions of southern Italy, the best parasite control and tomato yield performances were obtained with sulfonylureas (rimsulfuron and chlorsulfuron) applied through drip irrigation in pretransplant at 25.0 and 5.0 g a.i. ha^{-1}, and in post-transplant at 75.0 and 15.0 g a.i. ha^{-1}, respectively [23].

2.3 Agronomic methods

In order to integrate the use of chemical methods, there has been an increased effort to research suitable methods (fertilization, soil solarization, long-term rotation, soil management, sowing, or transplanting date) for the control of this parasitic weed, even because there is an increasing market for organically grown tomatoes, where the use of chemical pesticides is not an option [24].

2.3.1 Fertilization

Broomrape infestations occur mainly in soils poor nitrogen (0.2 and 1.8 ‰) and organic matter (1–2%) such as many soils of southern Italy [25], where the Italian research studies related in this chapter were carried out. Also, phosphate in deficient soil showed a suppressive effect of *P. ramosa* parasitism [26]. Therefore, soil fertility management can contribute to the management of this parasite. Phosphorous and nitrogen have been described to downregulate strigolactones exudation in some crop species [27–29].

Direct contact with fertilizer, such as urea and ammonium, may be toxic to broomrape, inhibiting seed germination and seedling growth [30]. Urea fertilizer, due to hydrolysis in soil, produces ammonium ion, which probably exerts the toxic effect on the parasite [31].

Nitrogen fertilizer (80 kg ha^{-1} N) or sulfur (8 t ha^{-1} S) applied prior to the tomato seedling transplant showed a suppressive effect on the seed germination of *Phelipanche* [32]. Also, the mixtures of chicken manure and sulfur significantly reduced the dry weight of *Orobanche* and increased eggplant and potato yield compared with the control [33].

Organic compounds are widely used in cropping systems to increase soil organic matter, structural stability, water holding and cation exchange capacities, and as a source of nutrients [34].

Recently, in the olive production and/or processing areas, as those of southern Italy, the use of oil mill wastewater (OMW) has been proposed as a suitable method for the containment of *P. ramosa.* In this regard, several trials dealing with the OMW distributed on the heavy infested soils at the dose of 80 m^3 ha^{-1}, 40 days prior to tomato seedling transplant (**Figure 6**), and incorporated into the soil later, revealed a significant reduction (between 34 and 76%) of emerged *P. ramosa* plants with respect to the untreated control (**Figure 7**), limiting the additional seed production of this parasite [35]. This could be due to the organic and mineral compounds, as nitrogen, phosphorus, and potassium contained in the OMW, which could improve the nutrient status of the tomato plants in addition to the effects of phenols present in the OMW that could produce a reduction of *P. ramosa* seed germination [36–38]. Therefore, the tomato marketable yield showed a significantly higher value in the OMW treatment than the untreated control. No significant differences for the fruit qualitative characteristics were observed [35].

Figure 6.
Mechanical distribution of OMW on the soil (F. Lops).

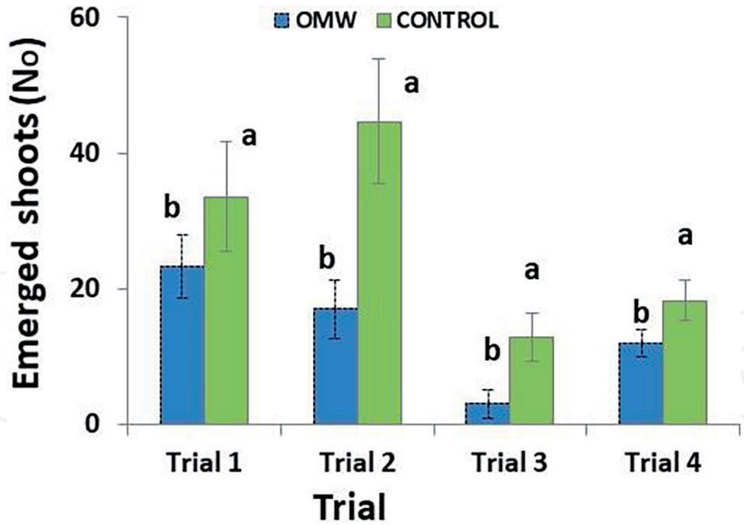

Figure 7.
Average number per m^{-2} of P. ramosa for OMW and control at the time of the tomato harvest in the different trials. Different letters indicate significant differences at $P < 0.05$ according to Tukey's test [35].

Furthermore, in recent years, the use of organic fertilizers or "plant biostimulant" compounds has encountered increasing interest in agriculture because they play roles in various soil and plant functions [39]. Some of these compounds of natural origin, such as natural amino acids, were also suggested for use in *P. ramosa* management strategies being able to inhibit seed germination [40, 41]. Experimental results in Italy indicated that using the commercial product "Radicon®" (a suspension-solution containing humic substances), at the time of transplanting (immersing the root of the seedlings in a 1.5% solution), and incorporating it into the soil in the first 3 irrigation interventions, produced a reductions of 68.1% of emerged shoots in comparison with the untreated control. These substances introduced into the soil rhizosphere can cause severe physiological disorders of the germinating *P. ramosa* seeds, thus reducing the number of developing tubercles of the parasite [42].

2.3.2 Soil solarization

Solarization is used in many warm climate countries, as pre-tomato planting treatment. Its consists of heating the soil through sun energy achieving temperatures above 45°C, by covering a wet soil with transparent polyethylene sheets for a period of 4–8 weeks during the warmest season [43]. This method for the high cost per surface unit is not readily applicable at large scale [44]. Solarization may be more effective if combined with added nitrogen fertilizers as chicken manure [45].

2.3.3 Rotation

Decreasing the frequency of tomato cultivation prevents *P. ramosa* seed bank increases, maintaining the seed bank dormant and reducing the rate of seed bank replenishing. However, it is a long-term strategy due to the long viability of seed bank [16], which requires at least a nine-course rotation in order to prevent broom-rape seed bank increases [46]. Its efficacy for broomrape cultural control can be increased including trap and/or catch crops as components in the rotation [16].

The trap crops are species (e.g., *Medicago sativa*, *Vigna unguiculata*, *Pisum sativum*, and *Linum usitatissimum*) whose root exudates induce broomrape seed germination, but these species do not allow attachment or support broomrape seedling growth and survival [47].

Catch crops are host plants that support normal parasitism, but they are harvested as green vegetables after the parasite seeds germinated and before the flowering and seed dispersal stages of the parasite itself. For instance, *Brassica campestris* when managed properly as a catch crop can result in up to a 30% reduction in the size of broomrape seed bank [48].

2.3.4 Soil management

The soil tillage management must aim at reducing the seed bank, while minimizing the production of new seeds. In this regard, inversion plowing results in burial of a large proportion of seed in the tillage layer, carrying them at a depth from which they cannot germinate, although they remain viable in the deep soil for a long period of time [49, 50]. Deep plowing has been suggested to bring seeds of parasitic weeds to a depth with less oxygen availability and therefore a reduction in its germination capacity [51, 52]. Eizenberg et al., 2007 observed that the deep plowing ≥ 12 cm strongly reduced broomrape infection severity in terms of number of parasites, total parasitic biomass, delayed broomrape emergence and prevention of flower initiation, and seed set. Results of another study [53], carried out in two heavily infested fields in southern Italy, showed significant lower parasite attachments on tomato roots, the lower dry weight of emerged and underground-branched shoots per host plant in 50 cm deep plowing compared with 30-cm-deep plowing (**Table 1**).

2.3.5 Sowing or transplanting date

The air and soil temperature are the main factors influencing the dynamic of host/parasite interaction and development. Temperature is strongly connected with the climatic conditions, which are themselves related to the periods for crops seedling into the field. Delayed sowing is consistently reported to reduce infection of winter crops such as oilseed rape [30]. Also, in spring-summer crops such as sunflower, modified planting dates provided the indirect effect of temperature on Orobanche parasitism [54]. In this regard, a study by Kebreab et al., 1999 [55] reports that at supra-optimal temperatures for germination of *O. crenata* seeds (i.e., above 25°C), they will not

Field trials	Plowing depth	Total attachments	Shoot (DW)	Tubercles
	(cm)	(no)	(g)	(g)
Field trial A	30	9.7 ± 2.4 a	56.9 ± 12.9 a	106.1 ± 11.8 a
	50	5.1 ± 1.5 b	29.9 ± 6.7 b	56.1 ± 8.2 b
Field trial B	30	12.8 ± 2.8 a	73.0 ± 16.4 a	140.7 ± 15.6 a
	50	7.9 ± 1.6 b	46.2 ± 10.4 b	87.4 ± 9.7 b
Average plowing depth	30	11.2 ± 2.6 a	64.9 ± 14.6 a	123.4 ± 9.0 b
	50	6.5 ± 1.5 b	38.0 ± 8.4 b	71.7 ± 8.9 b

Table 1.
Mean value ± SD of total attachments, dry weight of emerged shoots, and tubercles per tomato plant of 30-cm-deep plowing compared with 50 cm one. Different letters in each column of each field and plowing treatment are differing significantly at P ≤ 0.05, according to Tukey's test.

germinate. In a research carried out in southern Italy [14], a delay in seedling transplanting date from April to the hottest May reduced the *P. ramosa* infestation by 77%. Indeed, the daily maximum temperature was almost always below 25°C from April to mid-May, the period corresponding to the first stage of the tomato cycle for the early crop (transplant in April), while it increased to the threshold values always higher than 25°C starting from mid-May. This technique would give the host plant a time advantage over the *P. ramosa* and thereby make the tomato crop more competitive against this parasitic weed.

2.4 Biological methods

2.4.1 Bioherbicide

Biological agents such as pathogens *Fusarium* spp. (e.g., *Fusarium oxysporum* and *Fusarium arthrosporiodes*) or *Ulocladium botrytis,* incorporated into the soil by drip irrigation in field, are able to infect the pre-attached broomrape stages, and efficacy in reducing number and weight of emerging broomrapes [56, 57]. Due to the parasitic plant life cycle, multiple applications of *Fusarium* at the soil level would be necessary [58]. Conidial suspension of two *F. oxisporum* isolated reduced *O. crenata* and *P. ramosa* germination *in vitro* by 76–80%, in root chambers by 46–50%, and in polyethylene by 40–55% [59]. Fungi can be applied in the field together with solid growth media (such as wheat, corn, or rice grains) or in granules containing the biocontrol agent nutrients [60]. Compost activated by *Fusarium* was efficient in reducing the infection, by minimizing the number of parasitic spikes on the host tomato plant. This might be due to the additive effects on the seed germination of the parasite of the organic compound along with the soilborne fungi [61, 62]. Both granular soil applications and conidial suspensions of *Fusarium sp*. caused extensive mortality of *P. ramosa* in pot experiments. On the contrary, in field experiments, results were inconsistent as reduction *P. ramosa* shoot number and biomass [63, 64]. The main obstacle to the use and development of biocontrol agents is the poor field efficacy of the known pathogens. Soil-active biocontrol agents for *Phelipanche* must be able to contend with soil microorganisms without negatively affecting the host crop [65].

2.4.2 Resistant varieties

Cultivation of resistant varieties is another sustainable method to control *Phelipanche* [66, 67]. In addition, it is a useful component of an integrated approach, because easy to combine with other measures such as soil fertility amendments, land preparation, or soil tillage. Several mechanisms underlying the resistance of plants to the *P. ramosa* parasite have been described [68]. These include low stimulation of broomrape seed germination, pre-haustorial resistance, phytoalexin induction, high levels of peroxidase activities, lignification of host endodermis and xylem vessels, cell wall deposition, development of an encapsulation layer in the cortical parenchyma, induction of pathogenesis-related proteins, and sealing of host xylem vessels by deposition of mucilage [69]. Considered that this parasite requires stimulants exuded by the host roots, in order to germinate and reach the host root, varieties that exude stimulants at low levels or secrete inhibitors, they could be suitable for reducing parasite infection [70, 71]. An example of tomato cultivars resistant to *P. ramosa* infestation was reported by Qasem and Kasraw, 1995 [72]. The low germination stimulant phenotype of tomato has been reported in mutants owing to reduced exudation of strigolactones [73]. A successful screening program in a heavily broomrape-infested field, to locate a resistant tomato line from a fast neutron-mutagenized M2 tomato population, was reported in Israel [74]. However, at present there are no commercial varieties for the broomrape control in tomato [6]. Research is needed in this regard to select from the wide range of varieties resistant to this parasite.

2.5 Integrated method

The single control practices described above are often only partially effective and sometimes inconsistent. Therefore, the most feasible way of coping with the weedy root parasites is *via* the integration different preventive measures and control instruments on a long-term basis into the given farming system [75]. The real challenge is to integrate practices that obtain optimum efficiency in terms of reduction of existing seed banks, prevention of seed production, and avoidance of seed dissemination with affordable costs. A computer simulation on integrated approach with a selection of appropriate cultural methods such as hand weeding, trap/catch cropping, delayed planting, resistant cultivars, and solarization demonstrates the importance of preventing new seeds entering the soil seed bank [76]. Resistant crop varieties and delayed transplant, for instance, are generally considered the useful components of an integrated approach that are usually easy to combine with other measures such as rotation, soil fertility amendments, and land preparation or soil tillage, and suitable to promote tomato plant growth and to reduce the *P. ramosa* infestation. Advantages of these sustainable approaches are no chemical applications that are known to cause damage to the environment.

3. Conclusion

The spread of branched broomrape is of great concern in tomato and other susceptible crop production systems in many countries around the world. This review summarizes the main control measures for the weedy root parasites *Phelipanche* and *Orobanche* in processing tomato, namely prevention, chemical, agronomic, and biological control. Some of these methods are commercially widely used by farmers (herbicidal control), some are in the final stages of development toward commercialization (resistant varieties), and some still require further development and improvement before commercial implementation (bioherbicide control). As for chemical control of broomrape, it should take the environment into consideration by encouraging reductions of herbicides, by carefully calibration of doses and timing of treatments depending on the underground phenology of broomrape determined by local conditions. One of the most promising directions is the precision agriculture approach of site-specific weed management. In this approach, herbicide is applied only in the infested area according to the spatial variation of parasite infestation in the field. Furthermore, it is desirable to improve the environmentally friendly, sustainable, and practical parasite control methods and use them in an integrated way. Therefore, future efforts must aim at improving these parasite control methods in accordance with new cultivation technologies suitable for the development of the processing tomato.

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