HortScience 60(7):1058–1064. 2025. https://doi.org/10.21273/HORTSCI18497-25

Evaluating the Safety and Efficacy of Chemigation Alternatives for Branched Broomrape (*Phelipanche ramosa*) Control in Processing Tomatoes

Matthew Fatino
Department of Plant Sciences, University of California Davis, One Shields Avenue, Davis, CA 95616, USA

Juan Carlos Galaz
UC Davis Chile Life Sciences Innovation Center, Torre B - Av. Sta. María 2670, oficina 206, 7520424 Providencia, Región Metropolitana, Chile

Bradley D. Hanson
Department of Plant Sciences, University of California Davis, One Shields Avenue, Davis, CA 95616, USA

Keywords. acibenzolar-S-methyl, ALS inhibitors, chemigation, halosulfuron

Abstract. **Branched broomrape is an obligate parasite that can attach to the roots of a wide range of plants, particularly tomato and other agricultural crops. Interest in strategies for managing branched broomrape in processing tomatoes has been growing in California and Chile, where tomatoes are major cash crops. In Chile, branched broomrape has been spreading throughout tomato-growing regions for decades; in California, it is not yet widespread, but is a highly regulated quarantine pest. Multiple field trials were conducted in California and Chile during 2021 and 2022 to evaluate herbicide programs for crop safety and efficacy on branched broomrape. Sequential treatment approaches were based on an Israeli-developed program of preplant incorporated (PPI) sulfosulfuron, followed by several in-season chemigation treatments with imazapic. Additional treatments used imazamox or rimsulfuron as the chemigation herbicide alone or paired with PPI sulfosulfuron and a chemigated application of acibenzolar-S-methyl. In the crop safety experiments, visual phytotoxicity and yield data were recorded; in the efficacy trials, phytotoxicity and broomrape emergence data were collected. The Israeli program reduced broomrape emergence and did not injure tomatoes, but registration of imazapic for this use is unlikely in either California or Chile. In general, chemigated imazamox alone or paired with PPI sulfosulfuron reduced broomrape emergence; however, chemigated imazamox caused unacceptable crop injury in most trials at rates greater than 9.6 g a.i./ha. Three applications of chemigated rimsulfuron alone or paired with PPI sulfosulfuron reduced broomrape emergence and did not injure tomatoes. A 24(c) Special Local Needs label was approved in 2023 that allowed chemigated rimsulfuron in California tomatoes. Future research will focus on refining the rimsulfuron protocol under a wider range of production practices in California and on supporting approval of this use in Chile.**

Processing tomatoes are a major cash crop in the inland valley growing regions of California and Chile. In California, processing tomatoes are grown in the Sacramento and San Joaquin valleys and rank as the no. 10 crop in the state, worth more than US$1 billion per year (US Department of Agriculture 2023). In 2022, California growers produced 9.5 Mt of tomatoes on 90,000 ha, with an average yield of 105 $t \cdot ha^{-1}$ (US Department of Agriculture 2023). In Chile, processing tomatoes are grown in the O'Higgins and Maule regions of the Chilean Central Valley (Oficina de Estudios y Políticas, Agrarias 2021). In 2020, Chilean growers produced just less than 400,000 t of tomatoes on 7,773 ha, with an average yield of $\sim$50 $t \cdot ha^{-1}$ (Oficina de Estudios y Políticas, Agrarias 2021).

Broomrape (*Phelipanche* and *Orobanche*) is a parasitic weed native to the Mediterranean basin (Joel 2009; Musselman 1994). Broomrape is an obligate parasite that germinates only after receiving a chemical signal from a suitable host plant, after which seedlings then quickly attach to the roots of the host via a haustorium (Watts et al. 2024). The aboveground portion of the broomrape life cycle is relatively short. It consists of multiple flowering stems that lack chlorophyll and can quickly flower and produce thousands to hundreds of thousands of seeds that are highly persistent in the soil seedbank (Watts et al. 2024). Some broomrape species have specialized and narrow host ranges, whereas others, such as *Phelipanche ramosa* (branched broomrape) and *Phelipanche aegyptiaca* (Egyptian broomrape), have wide host ranges that include many agricultural crop families grown in California and throughout the world (Musselman 1994). Broomrape can cause severe economic losses in tomato cropping systems as a result of decline in vigor, with yield losses in severe infestations of more than 50% in other parts of the world (Osipitan et al. 2021).

In California, branched broomrape was first reported at the turn of the 20th century, but was thought to be eradicated through several decades of coordinated efforts by the processing tomato industry and state agencies (Gaimari and O'Donnell 2008; Jain and Foy 1989). However, in recent years it has been reported in several commercial processing tomato fields in Yolo County, and now presents a major threat to both regional and statewide production because of its regulatory status (Kelch 2017; Osipitan et al. 2021). Branched broomrape is an A-listed quarantine pest in California that could lead to crop destruction if found and reported in a commercial field. In addition to the loss of the crop in the reporting year, a hold order is placed that bars the planting of host crops for several more years, presenting affected growers with a massive cumulative economic loss (Miyao 2017). In Chile, where tomatoes are typically grown under annual contracts, fields infested heavily with branched broomrape often are simply no longer contracted for tomato production as a result of the incurred yield losses (Galaz JC, personal communication). Egyptian broomrape, which was reported in three fields in the Sacramento Valley, the only known instance of this pest in the United States, is a Q-listed pest and is subject to the same regulatory steps as an A-listed species (Miyao 2017).

Many species of broomrape are widespread throughout the Mediterranean basin (Musselman 1994). Through decades of applied research, researchers in Israel have evaluated numerous chemistries and application techniques, and have developed a decision support system and treatment protocol for management of Egyptian and branched broomrape in their processing tomato systems (Eizenberg and Goldwasser 2018; Eizenberg et al. 2004; Hershenhorn et al. 1998, 2009; Kotoula-Syka and Eleftherohorinos 1991). The PICKIT decision support system relies on a thermal time model (growing degree days) to predict broomrape phenological stages and, based on these predictions, acetolactate synthase (ALS) inhibitor herbicides are applied at very low rates at times intended to target specific broomrape life stages and attachment to the host crop (Eizenberg et al. 2012; Ephrath et al. 2012). The Israeli protocol for Egyptian and branched broomrape

Received for publication 6 Feb 2025. Accepted for publication 7 Apr 2025.
Published online 9 Jun 2025.
Funding sources for this work include the California Tomato Research Institute, a California Department of Food and Agriculture Specialty Crop Block Grant (22-0001-031-SF), and the US Department of Agriculture IR4 Program.
We acknowledge and thank Eric Schreiner and Schreiner Bros Farming, Gene Miyao, Zach Bagley, and Coby Goldwasser for their contributions to this project.
M.F. is the corresponding author. E-mail: matthew.fatino@gmail.com.

Table 1. Planting, harvest, growing degree targets, and actual application dates for California field studies.

Application	Crop safety 2021a	Crop safety 2021b	Crop safety 2022a	Crop safety 2022b	Efficacy 2022[i]
PPI	19 Apr	5 May	7 Apr	11 May	7 Apr
Transplant	28 Apr	12 May	13 Apr	19 May	3 May
400 GDD	20 May	4 Jun	21 May	4 Jun	26 May
500 GDD	27 May	9 Jun	26 May	14 Jun	1 Jun
600 GDD	2 Jun	15 Jun	31 May	21 Jun	6 Jun
700 GDD	7 Jun	22 Jun	3 Jun	24 Jun	12 Jun
800 GDD	10 Jun	24 Jun	8 Jun	1 Jul	16 Jun
900 GDD	16 Jun	29 Jun	14 Jun	11 Jul	23 Jun
Harvest	30 Sep	7 Oct	27 Sep	28 Sep	—

[i] The efficacy experiment was not harvested because of variability in crop yield caused by weekly scouting activity.

GDD = growing degree days; PPI = preplant incorporated.

Table 2. Treatments in two chemigation crop safety studies evaluating several herbicides on tomato crop safety in 2021 (Davis, CA, USA).

No.	Treatment	Rate (g a.i./ha)	Description	Application (GDD)
1	Grower standard[i]	—	—	—
2	Sulfosulfuron[ii]	37.5	PPI	—
	Imazapic	4.8	Chem × 5	400, 500, 600, 700, 800
3	Sulfosulfuron	37.5	PPI	—
4	Imazamox	9.6	Chem × 5	400, 500, 600, 700, 800
5	Imazamox	19.2	Chem × 5	400, 500, 600, 700, 800
6	Sulfosulfuron	37.5	PPI	—
	Imazamox	9.6	Chem × 5	400, 500, 600, 700, 800
7	Sulfosulfuron	37.5	PPI	—
	Imazamox	19.2	Chem × 5	400, 500, 600, 700, 800
8	Sulfosulfuron	37.5	PPI	—
	Imazamox	28.8	Chem × 5	400, 500, 600, 700, 800
9	Sulfosulfuron	37.5	PPI	—
	Imazamox	38.4	Chem × 5	400, 500, 600, 700, 800
10	Sulfosulfuron	37.5	PPI	—
	Imazamox, alternate timing	9.6	Chem × 5	500, 600, 700, 800, 900

[i] Grower standard in this location: 350 g a.i./ha *S*-metolachlor and 91.9 g a.i./ha trifluralin applied to all plots.

[ii] Israeli grower standard.

Chem × 5 = five chemigation applications; GDD = growing degree days; PPI = preplant incorporated.

control is based on sulfosulfuron, which is incorporated either mechanically or by overhead irrigation, followed by multiple chemigated applications of imazapic. However, because of significant regulatory barriers to registering imazapic in California, our chemigation research pivoted to imazamox, which already has a registration in California. Imazamox has been shown to manage other species of broomrape successfully in different crops as a foliar treatment and in herbicide-resistant crops such as imazamox-resistant canola (Eizenberg et al. 2006; Yanev et al. 2020). In addition, some researchers evaluated imazamox for Egyptian broomrape control and showed minor success in tomato in laboratory settings, and its constraints for use in tomato cropping rotations have been evaluated in some limited systems (Fatino et al. 2024; Monfared et al. 2016; Umiljendić et al. 2015).

Table 3. Treatments in two chemigation crop safety studies evaluating several herbicides on tomato crop safety in 2022 (Davis, CA, USA).

No.	Treatment	Rate (g a.i./ha)	Description	Application (GDD)
1	Grower standard[i]	—	—	—
2	Sulfosulfuron[ii]	37.5	PPI	—
	Imazapic	4.8	Chem × 5	400, 500, 600, 700, 800
3	Imazamox	9.6	Chem × 5	400, 500, 600, 700, 800
4	Imazamox	19.2	Chem × 5	400, 500, 600, 700, 800
5	Rimsulfuron	22.7	Chem × 3	400, 600, 800
6	Rimsulfuron	22.7	Foliar × 3	400, 600, 800
7	Sulfosulfuron	37.5	PPI	—
7	Imazamox	9.6	Chem × 3	400, 500, 600, 700, 800
8	Sulfosulfuron	37.5	PPI	—
	Imazamox	19.2	Chem × 5	400, 500, 600, 700, 800
9	Sulfosulfuron	37.5	PPI	—
	Rimsulfuron	22.7	Chem × 3	400, 600, 800
10	Sulfosulfuron	37.5	PPI	—
	Rimsulfuron	22.7	Foliar × 3	400, 600, 800
11	Acibenzolar-S-methyl	26.2	Chem × 6	400, 500, 600, 700, 800, 900
12	Acibenzolar-S-methyl	52.4	Chem × 6	400, 500, 600, 700, 800, 900

[i] Grower standard in this location: 350 g a.i./ha *S*-metolachlor and 91.9 g a.i./ha trifluralin applied to all plots.

[ii] Israeli grower standard.

× 3/× 5/× 6 = three/five/six chemigation applications; Chem = chemigation; Foliar = foliar-applied herbicide; GDD = growing degree days; PPI = preplant incorporated.

Field studies evaluating the crop safety and efficacy of imazamox on branched broomrape in tomato began in 2021 and continued in 2022 in Chile and California. In 2022, rimsulfuron was also evaluated as a foliar and chemigation treatment following positive results in Italian processing tomato systems (Conversa et al. 2017). In 2022, acibenzolar-S-methyl, a plant defense activator, was evaluated in California as a chemigation treatment following positive results reported on broomrape species in sunflower and rapeseed (Fan et al. 2007; Véronési et al. 2009). The objective of our studies was to evaluate tomato crop safety and efficacy on branched broomrape of Israeli-developed herbicide programs modified to include additional herbicides in California and Chile.

Materials and Methods

California crop safety 2021/2022. Four experiments were conducted in 2021 and 2022 to evaluate the crop safety of several herbicides used for branched broomrape control in processing tomatoes at the UC Davis Plant Sciences Field Facility near Davis, CA, USA (lat. 38°45′29.1″N, long. 121°46′15.0″W) (Table 1). The site did not contain broomrape; these experiments focused on crop safety of sulfosulfuron and imazamox in 2021 as well as rimsulfuron in 2022 (Tables 2 and 3). The soil at this site was a loam with 44% sand, 36% silt, and 20% clay; an organic matter content of 1.85%; and a pH of 7.40. Plots were 12 m long on 1.5-m beds, with one plant row in the center of each bed. Each bed had two 22-mm drip lines buried 30 cm deep in the center of the bed, with 0.6-L/h emitters spaced every 30 cm. One line ran the full length of the beds and was used for crop irrigation; the second line was ended at the beginning and end of each plot and was used to apply the chemigation treatments. A redundant water delivery system was constructed to deliver irrigation water to the secondary chemigation drip lines. Experiments were arranged in a randomized complete block design with four replications. Preplant-incorporated (PPI) herbicides were applied using a backpack sprayer equipped with a three-nozzle boom delivering 187 L·ha^{-1} with TeeJet AIXR 11002 nozzles. PPI treatments were incorporated mechanically with a power incorporator and bed shaper after application. 'HM 58841' processing tomatoes were transplanted mechanically at a 30-cm spacing. Tomatoes were managed according to the commercial production practices in the region (Hartz et al. 2008). Chemigation applications were made using carbon dioxide to deliver a chemigation solution into individual plots according to a growing degree day schedule similar to that of the PICKIT system

Fig. 1. Carbon dioxide pressurized chemigation system used in the California trials.

(Eizenberg and Goldwasser 2018) (Fig. 1). Herbicide solutions were mixed in 3-L bottles and injected into individual plots over 5 to 10 min, followed by 1 h of irrigation to flush the lines. Visual plant phytotoxicity (percentage of vigor reduction, stunting, and chlorosis) data were collected throughout the season. Fruit were harvested from a 1-m^2 section of a row in the middle of the experimental plot at commercial fruit maturity. Data from each study were analyzed separately with a one-way analysis of variance (ANOVA) followed by Tukey's honestly significant difference (HSD) test in RStudio v. 1.2.5033 (RStudio, Boston, MA, USA).

Chile efficacy 2021/2022. The 2021 experiment in Chile was conducted in a commercial field near Santa Cruz (lat. 34°39′57.2″S, long. 71°22′22.7″W), 180 km south of Santiago; the 2022 experiment was conducted in a commercial field near Pumanque (lat. 34°39′43.5″S, long. 71°45′42.5″W), 230 km from Santiago. Soil at the 2021 site was a clay with a pH of 6.2; the soil at the 2022 site was a sandy loam with a composition of 51% sand, 26% silt, and 23% clay; an organic matter content of 2.7%; and a pH of 6.0. Both experiments used randomized complete block designs with four replications. Individual plots consisted of a single 1.5-m bed and were 17 m long in 2021 and 20 m long in the 2022 experiment. Foliar and PPI herbicide applications were made using an 18-L high-pressure motorized backpack sprayer with a three-nozzle boom equipped with TeeJet 11015 nozzles delivering 200 L·ha^{-1}. Sulfosulfuron was incorporated mechanically before transplanting. In 2021, 'HMX7883' tomato plants were hand-transplanted on 19 Jan 2021 in a single-plant line with 25-cm spacing. This planting date, which was ~6 weeks later than typical for the region, was delayed as a result of logistical challenges related to project funding. Field sites for both 2021 trials had natural populations of branched broomrape; in the 2022 experiment, the experimental site was inoculated by hand with 3 g of *P. ramosa* seed per bed 1 week before planting. Each bed had a single 16.2-mm drip line on the soil surface, with 1.1 L·h^{-1} emitters spaced every 20 cm. 'H1657' tomato plants were hand-transplanted on 2 Dec 2021 in a single-plant row with 25-cm within-row spacing. Tomatoes in both trials were managed according to commercial production practices in the region. Chemigation treatments were applied using Venturi-type injectors, which use a pressure difference between the water line and the 20-L tank to draw a diluted herbicide solution into a connected valve that mixes it with water in the hose (Tables 4 and 5, Fig. 2). Broomrape emergence was monitored in each plot weekly between 12 Mar and 13 Apr 2021 in the 2021 trial, and between 3 Feb and 20 Mar 2022 in the 2022 trial. Fruit were harvested from the center 5 m of each plot on 19 May 2021, and yield was recorded. Fruit were also harvested in 2022, but the data were deemed unreliable as a result of late-season fruit theft. Data from each season were analyzed separately with a one-way ANOVA followed by Tukey's HSD test in RStudio v. 1.2.5033.

California efficacy 2022. Efficacy trials field-testing and validating PICKIT protocols and other herbicide treatments on branched broomrape in California began in 2020 in a commercial tomato field near Woodland, CA, USA (lat. 38°45′29.1″N, long. 121°46′15.0″W), that was first reported to be infested with branched broomrape in 2019. In the 2022 experiment, treatments were coordinated with the earlier Chilean experiment and focused on sulfosulfuron, imazamox, and rimsulfuron (Table 6). The soil at this site was a loam with 48% sand, 33% silt, and 19% clay; an organic matter content of 2.13%; and a pH of 7.20. Plots were 30-m-long; single, 1.5-m raised beds. Each bed had one 22-mm drip line buried 20 to 25 cm deep in the center of the bed, with 0.6 L·h^{-1} emitters spaced every 30 cm. The experiment was arranged in a randomized complete block design with four replications. 'HM 58841' processing tomato transplants were transplanted mechanically at a 30-cm spacing on 3 May 2022, with a later-planted treatment on 20 May 2022. Herbicides were applied according to the same protocols as the crop safety experiments, with chemigation applications applied according to a growing degree day schedule (Table 6). Visual plant phytotoxicity (percentage of vigor reduction, stunting, and chlorosis) data were collected, and broomrape emergence was monitored with clusters marked weekly between 26 Jun and 29 Aug 2022. After the last field scouting, the marked clusters were counted and recorded. Data were analyzed with a one-way ANOVA followed by Tukey's HSD test in RStudio v. 1.2.5033.

Table 4. Treatments from an efficacy study for branched broomrape management in 2021 (Santa Cruz, Chile).

No.	Treatment	Rate (g a.i./ha)	Description	Application (GDD)
1	Control	—	—	—
2	Sulfosulfuron[i]	37.5	PPI	—
	Imazapic	4.8	Chem × 5	400, 500, 600, 700, 800
3	Sulfosulfuron	37.5	Foliar × 3	200, 400, 600
4	Imazamox	9.6	Chem × 5	400, 500, 600, 700, 800
5	Imazamox	19.2	Chem × 5	400, 500, 600, 700, 800
6	Sulfosulfuron	37.5	PPI	—
	Imazamox	9.6	Chem × 5	400, 500, 600, 700, 800
7	Sulfosulfuron	37.5	PPI	—
	Imazamox	19.2	Chem × 5	400, 500, 600, 700, 800
8	Sulfosulfuron	37.5	PPI	—
	Imazamox	28.8	Chem × 5	400, 500, 600, 700, 800
9	Sulfosulfuron	37.5	PPI	—
	Imazamox	38.4	Chem × 5	400, 500, 600, 700, 800

[i] Israeli grower standard.

× 3/× 5 = three/five chemigation applications; Chem = chemigation; GDD = growing degree days; PPI = preplant incorporated.

Results

California crop safety. There were early signs of visual injury in plots treated with the higher imazamox rates in both 2021 crop safety studies (treatment nos. 5, 9, and 10; Table 7). Noted symptoms included stunting, pale-green and -gray plants, and general vigor reduction. Midway through the season, the plants appeared to grow out of the most severe injury symptoms (Table 7). There were no significant differences in marketable tomato yield among treatments in either experiment (Table 7). Tomato yield ranged from 12.9 to 21.7 kg·m^{-2} in the first experiment and 12.7 to 21.3 kg·m^{-2} in the second experiment (Table 7).

Based on the crop injury results from the 2021 trials, 28.8- and 38.4-g a.i./ha rates of imazamox were not included in the 2022 studies in either California or Chile.

There were no signs of visual injury from any herbicide treatment in either of the 2022 experiments (data not shown). In the first experiment, tomato yield ranged from 15.5 to 22.7 kg·m^{-2}; in the second experiment, tomato yield ranged from 13.8 to 20.8 kg·m^{-2}, and all treatments were statistically similar to the grower standard (Table 8).

Chile efficacy 2021. The first Chilean trial evaluated the efficacy and crop safety of chemigated imazamox up to 38.4 g a.i./ha for branched broomrape management. Individual broomrape shoots were counted in both Chilean trials (as opposed to the number of broomrape clusters counted in the California trials). Chemigated imazamox alone at 19.2 g a.i./ha; and chemigated imazamox at 19.2, 28.8, and 38.4 g a.i./ha paired with PPI sulfosulfuron; and chemigated imazapic paired with PPI sulfosulfuron reduced broomrape emergence significantly vs. the untreated control (Table 9). Chemigated imazamox at all rates, alone and paired with sulfosulfuron, injured tomatoes (data not shown) and reduced

Table 5. Treatments from an efficacy study for branched broomrape management in 2022 (Pumanque, Chile).

No.	Treatment	Rate (g a.i./ha)	Description	Application
1	Control	—	—	—
2	Sulfosulfuron[i]	37.5	PPI	—
	Imazapic	4.8	Chem × 3	20, 35, 45 DAT
3	Imazamox	9.6	Chem × 5	400, 500, 600, 700, 800 GDD
4	Imazamox	19.2	Chem × 5	400, 500, 600, 700, 800 GDD
5	Rimsulfuron	10	Chem × 3	20, 35, 45 DAT
6	Rimsulfuron	10	Foliar × 3	20, 35, 45 DAT
7	Sulfosulfuron	37.5	PPI	—
	Imazamox	9.6	Chem × 5	400, 500, 600, 700, 800 GDD
8	Sulfosulfuron	37.5	PPI	—
	Imazamox	19.2	Chem × 5	400, 500, 600, 700, 800 GDD
9	Sulfosulfuron	37.5	PPI	—
	Rimsulfuron	10	Chem × 3	20, 35, 45 DAT
10	Sulfosulfuron	37.5	PPI	—
	Rimsulfuron	10	Foliar × 3	20, 35, 45 DAT
11	Halosulfuron	37.7	Foliar × 2	—

[i] Israeli grower standard.

× 2/× 3/× 5 = two/three/five chemigation applications; Chem = chemigation; DAT = days after transplant; Foliar = foliar-applied herbicide; GDD = growing degree days; PPI = preplant incorporated.

tomato yield significantly compared with the control and with the Israeli standard treatment of PPI sulfosulfuron followed by chemigated imazapic (Table 9). Tomato yield was variable as a result of the delayed transplanting date; however, compared with the untreated control, tomato yield reduction was greatest in plots treated with the higher rates of imazamox (Table 9). The Israeli standard, PPI sulfosulfuron paired with chemigated imazapic, had the best performance overall, reducing broomrape emergence significantly, with yields similar to the untreated control (Table 9).

Chile efficacy 2022. The second Chilean research trial evaluated several combinations of herbicides for branched broomrape management. There were limited differences among treatments. Treatment 6 (rimsulfuron foliar) had more broomrape shoots than treatments 2 (PPI sulfosulfuron, chemigated imazapic) and 8 (PPI sulfosulfuron, chemigated imazamox) (Table 10). Chemigation treatments tended to have less broomrape emergence than foliar treatments, which had similar numbers of shoots as the control (Table 10). Tomato plants in plots treated with imazamox were injured and appeared to have fewer and smaller fruit; unfortunately, the yield data at this site were compromised by fruit theft late in season (data not shown). The Israeli standard treatment of PPI sulfosulfuron and chemigated imazapic had the lowest broomrape emergence, which supports the results of the 2021 trial in Chile and is consistent with previous research (Eizenberg and Goldwasser 2018).

Fig. 2. Venturi injection system used for chemigation treatments in the Chilean studies.

California efficacy 2022. Chemigated imazamox resulted in severe injury to tomatoes in this trial. Visual injury in some plots was as high as 59%, and symptoms included severe stunting, pale-gray and -green plants, lack of flowers, and overall vigor loss (Table 11). PPI and chemigated rimsulfuron did not cause crop injury (Table 11). There were significant differences in broomrape emergence among treatments (Table 11). Treatment 5 (19.2 g a.i./ha imazamox) had the lowest broomrape emergence, with an average of nine clusters per 30-m plot, whereas treatments 14 and 15 (26.2 and 52.4 g a.i./ha acibenzolar-S-methyl, respectively) had the highest emergence at 60 and 63 clusters per plot (Table 11). Given the severe injury in imazamox-treated plots, the best treatment overall was treatment 10 (PPI sulfosulfuron paired with chemigated rimsulfuron), which had significantly lower broomrape emergence than the control treatment (Table 11). Among chemigated rimsulfuron treatments, PPI sulfosulfuron paired with chemigated rimsulfuron (treatment 10) had numerically lower broomrape emergence than chemigated rimsulfuron alone (treatments 6, 16, and 17). Foliar rimsulfuron applied three times (treatments 7 and 11), which was (at the time) the only registered treatment in our study, had broomrape emergence that was similar to the control plots, with an average of 58 and 53 clusters per plot (Table 11).

Discussion

This research was conducted to evaluate the crop safety and efficacy of chemigation treatments of various chemistries based on the PICKIT system developed in Israel (Eizenberg and Goldwasser 2018). The PICKIT system is based on chemigated imazapic; however, because of regulatory barriers to imazapic, we focused on sulfosulfuron and imazamox in trials conducted from 2021 to 2022 in both Chile and California. Data from four full-season field experiments in two countries and additional separate laboratory studies indicate that imazamox performance was not as good as that reported with imazapic, and that the margin of crop safety with imazamox was insufficient for commercial use (Fatino et al. 2024).

Given the injury from imazamox, the best treatment from the California efficacy study was PPI sulfosulfuron paired with chemigated rimsulfuron. This is very promising for California growers, considering recent California Department of Pesticide Regulation approval of a 24(c) label for chemigated rimsulfuron following positive results from Italian research and the preliminary California efficacy trials (Conversa et al. 2017; Corteva Corporation 2022). This means that growers with suspected or at-risk fields were able to use the rimsulfuron protocol during the 2023 season. Although Israeli systems find greater success with applications of sulfosulfuron and imazapic as the ALS inhibitor chemigated component of their PICKIT decision support system, there does not seem to be a regulatory path forward for imazapic for this use pattern in either California or Chile. Future research will not include chemigated imazamox because of the unacceptably low margin of crop safety seen in the Chilean efficacy experiments and in the California crop safety and efficacy trials. Sulfosulfuron will continue to be pursued for registration in California as a PPI material for branched broomrape control. However, given its long soil residual activity, growers will need to factor in the effects of PPI sulfosulfuron on rotational crops within the tomato cropping systems in California (Fatino and Hanson 2022). In Israel, sulfosulfuron is applied both as a PPI material and as a broadcast foliar application that is incorporated with overhead irrigation (Eizenberg and Goldwasser 2018). Very few tomato fields in California in Chile use overhead irrigation and instead rely soley on surface (Chile) or subsurface (California) drip irrigation, so this alternative application technique is logistically challenging. Further research in Chile will evaluate higher rates of rimsulfuron, similar to those tested in California, with the goal of supporting a label amendment.

As of late 2022, California growers have an approved alternative for branched broomrape control in chemigated rimsulfuron. Ongoing research includes further refinement of these rimsulfuron-based protocols to improve efficacy and related research on equipment sanitation strategies to reduce the risk of spread of branched broomrape into new fields and between regions. As with any weed management program, relying on a single strategy can increase the probability of developing resistance, and future research will include the evaluation of additional chemistries and nonchemical practices to manage branched broomrape and reduce the risk of its spread

Table 6. Treatments from an efficacy trial evaluating several herbicides for branched broomrape control in processing tomatoes in 2022 (Woodland, CA, USA).

No.	Treatment	Application	Rate (g a.i./ha)	Timing	Note
1	Grower standard[i]	—	—	—	—
2	Delayed transplant	—	—	—	Late planting (20 May 2022)
3	Sulfosulfuron	PPI	37.5	PPI	Israeli standard PICKIT
	Imazapic	Chem × 5	4.8	400, 500, 600, 700, 800 GDD	—
4	Imazamox	Chem × 5	9.6	400, 500, 600, 700, 800 GDD	—
5	Imazamox	Chem × 5	19.2	400, 500, 600, 700, 800 GDD	—
6	Rimsulfuron	Chem × 3	22.7	400, 600, 800 GDD	—
7	Rimsulfuron	Foliar × 3	22.7	400, 600, 800 GDD	—
8	Sulfosulfuron	PPI	37.5	PPI	—
	Imazamox	Chem × 5	9.6	400, 500, 600, 700, 800 GDD	—
9	Sulfosulfuron	PPI	37.5	PPI	—
	Imazamox	Chem × 5	19.2	400, 500, 600, 700, 800 GDD	—
10	Sulfosulfuron	PPI	37.5	PPI	—
	Rimsulfuron	Chem × 3	22.7	400, 600, 800 GDD	—
11	Sulfosulfuron	PPI	37.5	PPI	—
	Rimsulfuron	Foliar × 3	22.7	400, 600, 800 GDD	—
12	Sulfosulfuron	PPI	37.5	PPI	Alternate timing
	Imazamox	Chem × 5	9.6	500, 600, 700, 800, 900 GDD	—
13	Sulfosulfuron	PPI	37.5	PPI	Alternate timing
	Imazamox	Chem × 5	19.2	500, 600, 700, 800, 900 GDD	—
14	Acibenzolar-S-methyl	Chem × 6	26.2	400, 500, 600, 700, 800, 900 GDD	—
15	Acibenzolar-S-methyl	Chem × 6	52.4	400, 500, 600, 700, 800, 900 GDD	—
16	Rimsulfuron	Chem × 3	12.5	400, 600, 800 GDD	—
17	Rimsulfuron	Chem × 3	22.7	30, 50, 70 DAT	CA 24(c) protocol

[i] Grower standard in this location: 350 g a.i./ha *S*-metolachlor and 91.9 g a.i./ha trifluralin applied to all plots.

× 3/× 5/× 6 = three/five/six chemigation applications; Chem = chemigation; DAT = days after transplant; Foliar = foliar-applied herbicide; GDD = growing degree days; PPI = preplant incorporated.

Table 7. Tomato crop injury and yield from two chemigation crop safety studies in 2021 (Davis, CA, USA).

		Expt. 1			Expt. 2		
No.	Treatment	Injury 40 DAT (%)	Injury 90 DAT (%)	Yield 30 Sep 2021 (kg·m^{-2})	Injury 48 DAT (%)	Injury 77 DAT (%)	Yield 7 Oct 2021 (kg·m^{-2})
1	Grower standard[i]	0	0	18.6	0 b[ii]	0	17.9
2	Sulfosulfuron/imazapic 9.6 g a.i./ha × 5[iii]	0	0	21.7	10 ab	0	18.2
3	Sulfosulfuron	0	0	19.0	0 b	0	21.3
4	Imazamox 9.6 g a.i./ha × 5	5	0	18.1	0 b	0	20.4
5	Imazamox 19.2 g a.i./ha × 5	23	0	21.1	18 ab	8	16.6
6	Sulfosulfuron/imazamox 9.6 g a.i./ha × 5	3	0	16.4	0 b	0	16.7
7	Sulfosulfuron/imazamox 19.2 g a.i./ha × 5	8	0	20.5	10 ab	3	18.1
8	Sulfosulfuron/imazamox 28.8 g a.i./ha × 5	15	0	12.9	23 ab	0	14.1
9	Sulfosulfuron/imazamox 38.4 g a.i./ha × 5	25	5	19.1	35 a	13	12.7
10	Sulfosulfuron/imazamox × 5 alternate timing	3	0	19.7	0 b	0	19.5
P value		0.07	0.4	0.7	0.01	0.2	0.2

[i] Grower standard in this location: 350 g a.i./ha *S*-metolachlor and 91.9 g a.i./ha trifluralin applied to all plots.

[ii] Means with the same letter in the same column are not significantly different according to Tukey's honestly significant difference test ($\alpha = 0.05$).

[iii] Israeli grower standard.

× 5 = five chemigation applications; DAT = days after transplant.

Table 8. Tomato yield from two chemigation crop safety studies in 2022 (Davis, CA, USA).

No.	Treatment	Expt. 1 yield 27 Sep 2022 (kg·m^{-2})	Expt. 2 yield 28 Sep 2022 (kg·m^{-2})
1	Grower standard[i]	19.3	15.1
2	Sulfosulfuron PPI/imazapic × 5[ii]	16.1	16.0
3	Imazamox 9.6 g a.i./ha × 5	22.7	20.8
4	Imazamox 19.2 g a.i./ha × 5	21.7	15.3
5	Rimsulfuron chemigated × 3	19.5	16.2
6	Rimsulfuron foliar × 3	15.8	15.9
7	Sulfosulfuron PPI/imazamox 9.6 g a.i./ha × 5	15.5	14.2
8	Sulfosulfuron PPI/imazamox 19.2 g a.i./ha × 5	17.2	17.4
9	Sulfosulfuron PPI/rimsulfuron chemigated × 3	21.4	18.9
10	Sulfosulfuron PPI/rimsulfuron foliar × 3	20.1	18.7
11	Acibenzolar-S-methyl 26.2 g a.i./ha × 6	16.5	18.4
12	Acibenzolar-S-methyl 52.4 g a.i./ha × 6	18.2	13.8
P value		0.12	0.2

[i] Grower standard in this location: 350 g a.i./ha *S*-metolachlor and 91.9 g a.i./ha trifluralin applied to all plots.

[ii] Israeli grower standard.

× 3/× 5/× 6 = three/five/six chemigation applications; Foliar = foliar-applied herbicide; PPI = preplant incorporated.

throughout California tomato-growing regions. Because of their regulatory status, broomrapes are of utmost concern for California tomato growers and regulatory agencies to, the extent that in 2024, the state appointed a Broomrape Program Board to recommend actions and guide the response to this pest (California Department of Food and Agriculture 2024). In the case of Chile, broomrape is not a quarantine pest, but has significant impacts on tomato production and land available to produce sensitive host crops. In both countries, it will be necessary to use management strategies that combine the application of chemical products with practices that prevent branched broomrape seed dispersion to other fields, and cultural practices that deplete the weed seedbank of branched broomrape seeds.

Table 9. Broomrape shoot emergence and tomato yield in response to several herbicide treatments in 2021 (Santa Cruz, Chile).

No.	Treatment	Broomrape (shoots/17-m plot)	Yield (kg/17-m plot)
1	Control	129 a[i]	27.8 ab
2	Sulfosulfuron (37.5 g a.i./ha, PPI) + imazapic (4.8 g a.i./ha, chem × 5)[ii]	20 bc	32.7 a
3	Sulfosulfuron (37.5 g a.i./ha, PPI) + sulfosulfuron (37.5 g a.i./ha, foliar × 3)	67 a–c	7.7 de
4	Imazamox (9.6 g a.i./ha, chem × 5)	82 ab	5.6 de
5	Imazamox (19.2 g a.i./ha, chem × 5)	22 bc	13.8 cd
6	Sulfosulfuron (37.5 g a.i./ha, PPI) + imazamox (9.6 g a.i./ha, chem × 5)	10 c	5.1 e
7	Sulfosulfuron (37.5 g a.i./ha, PPI) + imazamox (19.2 g a.i./ha, chem × 5)	25 bc	21.2 bc
8	Sulfosulfuron (37.5 g a.i./ha, PPI) + imazamox (28.8 g a.i./ha, chem × 5)	6 c	2.9 e
9	Sulfosulfuron (37.5 g a.i./ha, PPI) + imazamox (38.4 g a.i./ha, chem × 5)	13 c	3.2 e
P value		0.006	>0.0001

[i] Means with the same letter in the same column are not significantly different according to Tukey's honestly significant difference test (α = 0.05).
[ii] Israeli grower standard.
× 3 = three applications at 200, 400, 600 growing degree days; × 5 = five applications at 400, 500, 600, 700, 800 growing degree days; chem = chemigated; foliar = foliar-applied herbicide; PPI = preplant incorporated.

Table 10. Branched broomrape shoot emergence in response to several herbicide treatments in 2022 (Pumanque, Chile).

No.	Treatment	Broomrape shoots/20-m plot
1	Control treatment	407 ab[i]
2	Sulfosulfuron (37.5 g a.i./ha, PPI) + imazapic (4.8 g a.i./ha, chem × 5)[ii]	24 b
3	Imazamox (9.6 g a.i./ha, chem × 5)	160 ab
4	Imazamox (19.2 g a.i./ha, chem × 5)	58 ab
5	Rimsulfuron (10 g a.i./ha, chem × 3)	290 ab
6	Rimsulfuron (10 g a.i./ha, foliar × 3)	710 a
7	Sulfosulfuron (37.5 g a.i./ha, PPI) + imazamox (9.6 g a.i./ha, chem × 5)	63 ab
8	Sulfosulfuron (37.5 g a.i./ha, PPI) + imazamox (19.2 g a.i./ha, chem × 5)	36 b
9	Sulfosulfuron (37.5 g a.i./ha, PPI) + rimsulfuron (10 g a.i./ha, chem × 3)	161 ab
10	Sulfosulfuron (37.5 g a.i./ha, PPI) + rimsulfuron (10 g a.i./ha, foliar × 3)	411 ab
11	Halosulfuron, (37.7 g a.i./ha, foliar × 2)	309 ab
P value		0.0008

[i] Means with the same letter in the same column are not significantly different according to Tukey's honestly significant difference test (α = 0.05).
[ii] Israeli grower standard.
× 3 = three applications at 200, 400, 600 growing degree days; × 5 = five applications at 400, 500, 600, 700, 800 growing degree days; chem = chemigated; foliar = foliar-applied herbicide; PPI = preplant incorporated.

Table 11. Visual crop injury ratings and average number of branched broomrape clusters in an efficacy trial in a heavily infested commercial tomato field in 2022 (Woodland, CA, USA).

No.	Treatment	Application	Rate (g a.i./ha)	Avg clusters/36-m row	Injury (%)
1	Control	—	—	52 a–c[i]	16 bc
2	Delayed transplant	—	—	25 b–d	15 bc
3	Sulfosulfuron[ii]	PPI	37.5	18 cd	0 c
	Imazapic	Chem × 5	4.8	—	—
4	Imazamox	Chem × 5	9.6	16 cd	46 a
5	Imazamox	Chem × 5	19.2	9 d	54 a
6	Rimsulfuron	Chem × 3	22.7	18 cd	1 c
7	Rimsulfuron	Foliar × 3	22.7	58 ab	1 c
8	Sulfosulfuron	PPI	37.5	20 cd	45 ab
	Imazamox	Chem × 5	9.6	—	—
9	Sulfosulfuron	PPI	37.5	15 d	59 a
	Imazamox	Chem × 5	19.2	—	—
10	Sulfosulfuron	PPI	37.5	15 d	0 c
	Rimsulfuron	Chem × 3	22.7	—	—
11	Sulfosulfuron	PPI	37.5	53 a–c	0 c
	Rimsulfuron	Foliar × 3	22.7	—	—
12	Sulfosulfuron	PPI	37.5	23 b–d	39 ab
	Imazamox	Chem × 5	9.6	—	—
13	Sulfosulfuron	PPI	37.5	16 cd	49 a
	Imazamox	Chem × 5	19.2	—	—
14	Acibenzolar-S-methyl	Chem × 6	26.2	60 ab	0 c
15	Acibenzolar-S-methyl	Chem × 6	52.4	63 a	0 c
16	Rimsulfuron	Chem × 3	12.5	27 a–d	0 c
17	Rimsulfuron	Chem × 3	22.7	24 b–d	0 c
P value				> 0.0001	> 0.0001

[i] Means with the same letter are not significantly different from one another according to Tukey's honestly significant difference test (α = 0.05).
[ii] California grower standard: 350 g a.i./ha *S*-metolachlor and 91.9 g a.i./ha trifluralin applied.
× 3/× 5/× 6 = three/five/six chemigation applications; Chem = chemigation; PPI = preplant incorporated.

References Cited

California Department of Food and Agriculture. 2024. Broomrape program. https://www.cdfa.ca.gov/plant/ipc/broomrape/. [accessed 12 Jan 2025].

Conversa G, Bonasia A, Elia A. 2017. Chemical control of branched broomrape in processing tomato using sulfonylureas in southern Italy. Ital Agron. 12(3):939. https://doi.org/10.4081/ija.2017.939.

Corteva Corporation. 2022. Matrix SG herbicide product label. Corteva publication no. R268-016. Corteva Corporation, Indianapolis, IN, USA.

Eizenberg H, Aly R, Cohen Y. 2012. Technologies for smart chemical control of broomrape (*Orobanche* spp. and *Phelipanche* spp.). Weed Sci. 60(2):316–323. https://doi.org/10.1614/WS-D-11-00120.1.

Eizenberg H, Colquhoun JB, Mallory-Smith CA. 2006. Imazamox application timing for small broomrape (*Orobanche minor*) control in red clover. Weed Sci. 54(5):923–927. https://doi.org/10.1614/WS-05-151R.1.

Eizenberg H, Goldwasser Y. 2018. Control of Egyptian broomrape in processing tomato: A summary of 20 years of research and successful implementation. Plant Dis. 102(8):1477–1488. https://doi.org/10.1094/PDIS-01-18-0020-FE.

Eizenberg H, Goldwasser Y, Golan S, Plakhine D, Hershenhorn J. 2004. Egyptian broomrape (*Orobanche aegyptiaca*) control in tomato with sulfonylurea herbicides: Greenhouse studies. Weed Technol. 18(3):490–496. https://doi.org/10.1614/WT-03-023R3.

Ephrath J, Hershenhorn J, Achdari G, Bringer S, Eizenberg H. 2012. Use of logistic equation for detection of the initial parasitism phase of Egyptian broomrape (*Phelipanche aegyptiaca*) in tomato. Weed Sci. 60(1):57–63. https://doi.org/10.1614/WS-D-11-00070.1.

Fan Z-W, Buschmann H, Müller-Stöver D, Sauerborn J. 2007. Main effects and interactions among acibenzolar-S-methyl, a biocontrol fungus and sunflower cultivar on control of *Orobanche cumana* Wallr. J Plant Dis Prot. 114(2):76–81. https://doi.org/10.1007/BF03356207.

Fatino M, Hanson B. 2022. Evaluating branched broomrape (*Phelipanche ramosa*) management strategies in California processing tomato (*Solanum lycopersicum*). Plants. 11(3):438. https://doi.org/10.3390/plants11030438.

Fatino M, Martin K, Dayan F, Hanson B. 2024. Adsorption of imazamox in California agricultural soils and implications for branched broomrape (*Phelipanche ramosa*) management. J Environ Sci Health B. 59(10):636–641. https://doi.org/10.1080/03601234.2024.2406123.

Gaimari S, O'Donnell M. 2008. California Department of Food and Agriculture, Sacramento, CA (vol 25).

Hartz T, Miyao G, Mickler J, LeStrange M, Stoddard S, Nunez J, Aegerter B. 2005. Processing tomato production in California. Division of Agriculture and Natural Resources publication no. 7288. UC ANR, Oakland, CA.

Hershenhorn J, Eizenberg H, Dor E, Kapulnik Y, Goldwasser Y. 2009. *Phelipanche aegyptiaca* management in tomato. Weed Res. 49(Supp 1):34–47. https://doi.org/10.1111/j.1365-3180.2009.00739.x.

Hershenhorn J, Goldwasser Y, Plakhine D, Ali R, Blumenfeld T, Bucsbaum H, Herzlinger G, Golan S, Chilf T, Eizenberg H, Dor E, Kleifeld Y. 1998. *Orobanche aegyptiaca* control in tomato fields with sulfonylurea herbicides. Weed Res. 38(5):343–349. https://doi.org/10.1046/j.1365-3180.1998.00105.x.

Jain R, Foy CL. 1989. Broomrapes (*Orobanche* spp.): A potential threat to U.S. broadleaf crops. Weed Technol. 3(4):608–614. https://doi.org/10.1017/S0890037X00032899.

Joel DM. 2009. The new nomenclature of *Orobanche* and *Phelipanche*. Weed Res. 49(Supp 1):6–7. https://doi.org/10.1111/j.1365-3180.2009.00748.x.

Kelch D. 2017. Branched Broomrape | *Orobanche ramosa*: Pest rating proposals and final ratings. https://blogs.cdfa.ca.gov/Section3162/?p=3853. [accessed 12 Jan 2025].

Kotoula-Syka E, Eleftherohorinos IG. 1991. *Orobanche ramosa* L. (broomrape) control in tomato (*Lycopersicon esculentum* Mill.) with chlorsulfuron, glyphosate and imazaquin. Weed Res. 31(1):19–27. https://doi.org/10.1111/j.1365-3180.1991.tb01738.x.

Miyao G. 2017. Egyptian broomrape eradication effort in California: A progress report on the joint effort of regulators, university, tomato growers and processors. Acta Hortic. 1159: 139–142. https://doi.org/10.17660/ActaHortic.2017.1159.21.

Monfared EK, Tokasi S, Aval MB, Ghanbari A, Mashhadi HR, Kudsk PN. 2016. Effect of rimsulfuron, imazapic and imazamox herbicides on broomrape (*Orobanche aegyptiaca*) in tomato (*Lycopersicum esculentum*). J Crop Ecophys. 9(36):645–660.

Musselman LJ. 1994. Parasitic weeds of the world: Biology and controls. Econ Bot. 48(3):332. https://doi.org/10.1007/BF02862335.

Oficina de Estudios y Políticas, Agrarias. 2021. En Chile y en el mundo el cultivo de tomate ha ido creciendo a la par con su mayor consumo. https://www.odepa.gob.cl/publicaciones/noticias/agro-en-la-prensa/en-chile-y-en-el-mundo-el-cultivo-de-tomate-ha-ido-creciendo-a-la-par-con-su-mayor-consumo. [accessed 12 Dec 2023].

Osipitan OA, Hanson BD, Goldwasser Y, Fatino M, Mesgaran MB. 2021. The potential threat of branched broomrape for California processing tomato: A review. Calif Agric. 75(2):64–73. https://doi.org/10.3733/ca2021a0012.

Umiljendić JG, Sarić-Krsmanović M, Šantrić L, Radivojević L. 2015. The effect of soil type on imazamox phytotoxicity to tomato. Pestic Phytomed. 30(4):217–224. https://doi.org/10.2298/PIF1504217G.

US Department of Agriculture. 2023. 2023 California processing tomato report. USDA National Agricultural Statistics Service, Washington, DC.

Véronési C, Delavault P, Simier P. 2009. Acibenzolar-S-methyl induces resistance in oilseed rape (*Brassica napus* L.) against branched broomrape (*Orobanche ramosa* L.). Crop Prot. 28(1):104–108. https://doi.org/10.1016/j.cropro.2008.08.014.

Watts A, Raipuria RK, Chaudhary A, Chauhan M, Joshi K, Singh N, Bhattacharya R. 2024. *Orobanche ramosa* (branched Broomrape). CABI Compendium. 38(4):329–343. https://doi.org/10.1079/cabicompendium.37747.

Yanev M, Mitkov A, Neshev N, Tonev T, Agricultural University 2020. Broomrape (*Phelipanche ramosa* (L.) Pomel) control in winter oilseed rape with imazamox-containing herbicide products. Int J Innov Approach Agric Res. 4(2):251–258. https://doi.org/10.29329/ijiaar.2020.254.9.