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ORIGINAL PAPER

Weed Control, Growth, and Yield of Tomato After Application of Metribuzin and Different Pendimethalin Products in Upper Egypt

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Abstract
Weeds are very problematic for tomato production worldwide. Differences in formulations of the same herbicide have different effects on weeds and crops. There are no published studies on the effect of the capsule suspension of pendimethalin (Pend) products on tomato in Egypt. The present study aims at evaluating three pre-plant Pend products compared with a post-plant metribuzin (Met) and hand hoeing on their efficiency on weed control and on the growth, yield, yield attributes, stand loss rate of tomato plants, and their economic benefit implications in tomato production. During the fall-winter seasons of 2019/2020 and 2020/2021, six weed control treatments were studied including three pre-plant Pend products, a post-plant Met, hand hoeing, and un-weeded control in tomato field experiments. Weed density, fresh weight [FW], and FW reduction% were measured. Tomato measurements included stand loss rate, vegetative growth parameters, leaf chlorophyll concentration, fruit diameter and length, marketable and total yields, fruit total soluble solids, and pH. All herbicides and hand hoeing treatments significantly reduced weeds FW. Stand loss rates of tomato were 0% in hand hoeing followed by Sencor (~9.3–11.1%). Vegetative growth and leaf chlorophyll concentration were improved in all treated plots as compared to the control. The highest significant increases in tomato branch number, plant height, stem diameter, and shoot FW were observed in Sencor and Mostmicro treatments. The highest marketable and total fruit yields were observed with Sencor. Met had the highest benefit–cost ratio in the study. All herbicides were effective against various noxious weeds, but tomato "hybrid 65,010" was more tolerant to Met which resulted in better yields than those obtained with Pend products. The most cost-effective method of weed control was Met.

Keywords *Solanum lycopersicum* · Herbicides · Hand hoeing · Plant stand loss · Vegetative growth · Marketable and total yield

1 Introduction

Tomato (*Solanum lycopersicum* L., Fam. Solanaceae) continues to be the second most economically important vegetable after potato in the world (FAOSTAT 2019; Ayuso-Yuste et al. 2022). Tomato products are widely used in the daily human nutrition being a rich source of many important health-promoting bioactive ingredients such as vitamins, phenolic compounds, ascorbic acid, and carotenoids, which are a vital source of lycopene (Quinet et al. 2019). These bioactive compounds, particularly lycopene, can help reduce cancers and cardiovascular diseases (Quinet et al. 2019). Egypt is among the top five tomato producers worldwide and is the first in Africa (Siam and Abdelhakim 2018). Tomatoes are cultivated in all governorates of Egypt including the Nile valley, delta region, and in reclaimed lands in six to seven growing seasons around the year (Siam and Abdelhakim 2018).

Harmful weeds can compete with tomato plants for the essential, yet limited resources (i.e., carbon dioxide, minerals, sunlight, and water) for crop growth. Consequently, weeds can considerably reduce tomato yield by 36–92% (Armelina 1983; Samant and Prusty 2014) and damage the fruit quality and their market value (Mennan et al. 2020).

Chemical control (by applying herbicides) is more effective than non-chemical weed control strategies (such as hand hoeing and mulching) in controlling harmful weeds in vegetable production systems (Mennan et al. 2020;

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Mohseni-moghadam and Doohan 2017). Therefore, various herbicides such as halosulfuron, S-metolachlor, fomesafen, and metribuzin (Met) are recommended to be used as pre- and post-transplant compounds in tomato cultivation worldwide (Kemble 2014; Mohseni-moghadam and Doohan 2017).

Met is a systemic selective herbicide of the asymmetrical triazines class that inhibits photosynthesis in target weeds (LeBaron et al. 2008). It is applied during pre- and post-emergence periods on a wide range of agronomic and vegetable crops (mainly tomato and potato) for the control of various dicot and monocot weeds (LeBaron et al. 2008). The herbicide, pendimethalin (Pend), is a dinitroaniline agent that halts cell division in weeds. It is extensively applied as an effective pre-emergence herbicide against annual weeds in more than 20 crops, including tomato (APCE 2018; Tetteh et al. 2011).

The highly potent effects of Pend and Met against many harmful weeds were confirmed in several crops, including tomato (Smith 2004). However, phytotoxic effects of Pend have been reported on various vegetable crops such as cabbage and onion (Miller et al. 2003; Smith 2004). Met can also cause injury to tomato and potato plants, which are more sensitive to the herbicide injury particularly under certain stress conditions (Chaudhari et al. 2017; Hatterman-Valenti et al. 1994).

In Egypt, Pend (labeled as Metha-Tomp® 33% emulsifiable concentrate (EC), 4.76 L ha^{-1}, and Grostop® 50% EC, 4.05 L ha^{-1}) and Met are the only registered pre- and post-emergent herbicides, respectively, for weed control in transplanted tomato fields according to APCE (2018). Unfortunately, Metha-Tomp® 33% EC caused a 30% injury to a tomato hybrid cv "65,010" grown in Assiut region, which is one of the largest producers of tomatoes in Egypt during the fall-winter seasons (Mohamed 2019). Grostop 50% EC is rarely available for farmers in pesticide markets in Assiut.

It is known that the differences in formulations of the same herbicide can substantially affect both the compound efficacy on weeds and the level of injury to the crop plants (Grey and Webster 2013). Capsule suspension of Pend products (such as Respect 45%, Stop 45%, and Mostmicro 36.5%) was recently registered in some vegetable crops such as potato, sweet potato, vigna, common bean, and pea. Until now, there are no published studies on the effect of the pre-emergence application of the capsule suspension of Pend products on tomato in Egypt, especially a tomato hybrid cv "65,010" which showed relative sensitivity to Pend in the form of EC (Metha-Tomp® 33% EC).

Therefore, the present study aims to investigate the effects of three different pre-plant Pend products (Respect 45% CS, 4.76 L ha^{-1}; Stop 45% CS, 4.05 L ha^{-1}; and Mostmicro 36.5% CS, 4.76 L ha^{-1}) compared with a post-plant Met product (Sencor 70% WP, 714.20 g ha^{-1}) and hand hoeing on:

1- Annual weed management efficiency
2- Plant growth, yield, yield attributes, and stand loss rate of tomato hybrid cv "65,010"
3- Economic benefit implications in tomato production in Upper Egypt

2 Materials and Methods

2.1 Growth Conditions, Treatments, and Design of Experiment

Two-field experiments were conducted consecutively during the fall-winter seasons from September to March of 2019/2020 (SI) and 2020/2021 (SII) at the Research Farm of the Faculty of Agriculture, Assiut University, Assiut governorate (82.56°W, 35.43°N, elevation 170 ft), Egypt. Maximum and minimum temperatures of the field growing conditions during SI and SII seasons are presented in Fig. 1. Seedlings of a tomato hybrid cv "65,010" (Syngenta Crop Protection, Egypt) were used. The hybrid has a very strong vegetative growth habit which covers the fruits well. Fruits have bright red color, are spherical in shape, and are firm with an excellent consistency in shape and size.

Tomato seeds were direct-sown in seedling polystyrene trays filled with a mixture of a peat and vermiculite (1:1, v:v) and grown in a greenhouse for 35 days at a private nursery specialized in transplant production in Assiut. Uniform tomato transplants were then manually transplanted into individual plots (4.6 m long × 3.6 m wide) that have clay soil at 60-cm distance between transplants with an approximate row spacing of 0.47 m on the 5th and 30th of September of both seasons. Planting density was 1.66 plants/m^2. Individual plots were planted with 18 tomato seedlings divided into 3 beds. Field agricultural practices including irrigation and fertilization were applied according to the standard agricultural recommendations by the Egyptian Ministry of Agriculture and Land Reclamation for tomato production in Egypt. During soil preparation, organic fertilizer (cow manure) was applied at the rate of 25 m^3 ha^{-1}. Application of ~ 150 units of P of calcium superphosphate (15.5% P_2O_5) was added during soil preparation and at 20 days after transplanting (DAT) the tomato plants. Potassium sulfate (48% K_2O) was added at the rate of ~ 350 units ha^{-1} K_2O, applied at 20 and 45 DAT. N fertilizer was applied in the form of ammonium sulfate (20.6% N) at the rate of ~ 100 units of N ha^{-1} at 20 DAT. N fertilizer was also applied in the form of ammonium nitrate (33.5% N) at the rate of ~ 280 units of N ha^{-1} and was divided into three equal portions at 45, 65, and 85 DAT. Magnesium sulfate (16% $MgSO_4$) was applied at the rate of 9.5 units ha^{-1} after 65 DAT.

Treatments consisted of three pre-plant pendimethalin (Pend) products [Mostmicro 36.5% CS, 4.76 L ha^{-1} (Sipcam

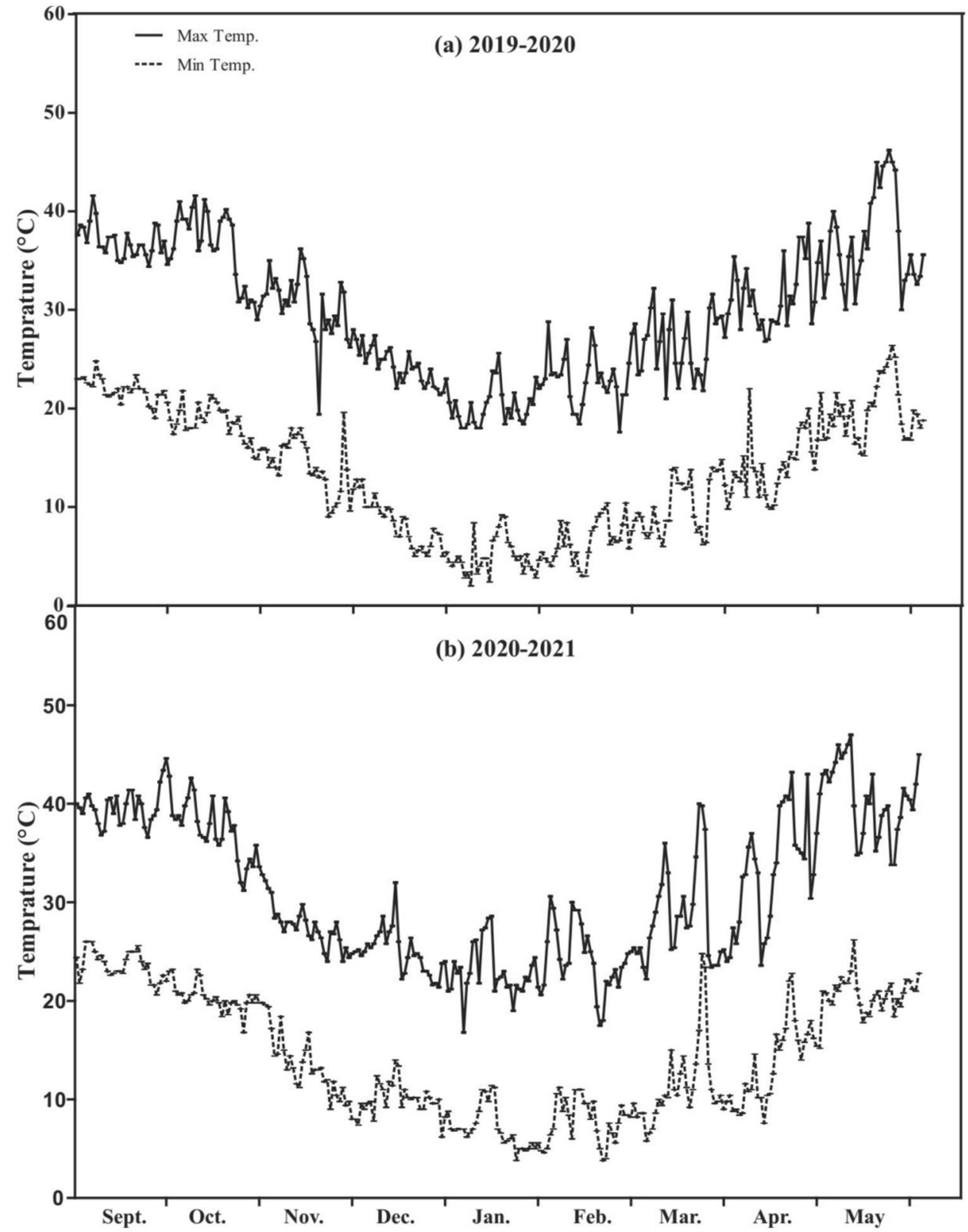

Fig. 1 Maximum and minimum temperatures during tomato field growing seasons of 2019/2020 (SI) and 2020/2021 (SII) seasons

Inagra SA, Spain); Respect 45% CS, 4.76 L ha^{-1} (StarChem Industrial Chemicals, Egypt); and Stop 45% CS at 4.05 L ha^{-1} (Nanjing Good Agro Co. Ltd., China)], a post-plant Met (Sencor 70% WP at 714.20 g ha^{-1}, Bayer Crop Sciences Ltd., Egypt), hand hoeing (applied twice at 20 and 40 DAT), and un-weeded control. Thus, the total number of treatments was six. Pend was applied directly on bare soil before irrigation and transplanting of tomato seedlings. Met was applied 2 weeks after tomato transplanting. The studied herbicides were dissolved in 476.19 L ha^{-1} water and applied using an electric knapsack sprayer (Model CF-20C-UD) with a single nozzle. The treatments of the experiments were organized in a strip plot design with three replications in both seasons.

2.2 Weed Species Associated with Tomato

The annual broad-leaved and grass weed species in the field trails' plots were identified, counted, and randomly harvested from one m^{-2} sections at 42 and 98 days after transplanting (DAT). Shoot fresh weight (FW, g m^{-2}) of each weed species was measured in the two seasons. Weed control efficacy of the former herbicides and hand hoeing was calculated from biomass data of fresh weeds using the following formula: weed control efficacy (%) = [(FW of weed in un-weeded control plot – FW of weed in treated plot) ÷ FW of weed in un-weeded control plot] × 100 (Yadav et al. 2015).

2.3 Measurement of Plant Stand Loss Rate

Tomato plant stand loss rate was visually assessed from all tomato plants in each treatment/plot of the trails by calculating [(total number of plants in the plot – number of plants that survived in the plot) ÷ total number of plants in the plot] × 100. This assessment was performed twice, at the 42nd DAT and at the 98th DAT directly before the first harvest process.

2.4 Vegetative Growth Measurements

Various growth characteristics were determined from 9 tomato plants in each experimental treatment in both seasons. Tomato plant height (cm) and stem diameter (mm) were measured using a meter ruler and a Vernier caliper, respectively. Number of branches per plant was then counted. At harvest, shoot fresh weight (FW, g) was recorded, and then, shoots were air dried for 15 days and then placed in an oven at 70 °C for 24 h to determine their dry weight (DW, g). Tomato relative leaf chlorophyll content was measured with the use of a chlorophyll meter (SPAD-502, Minolta, Japan) on the top fourth leaf of 3 plants/experimental plot/treatment ($n = 9$). Chlorophyll concentration was calculated from SPAD value using a linear model equation of $y = 0.0647x - 1.4543$ where y = chlorophyll content and x = SPAD value (Jiang et al. 2017).

2.5 Fruit Yield, Yield Attributes, and Fruit Quality Measurements

Manual harvest of tomato fruits was started in the second week of February (~ 126 DAT) until the last week of March in the two seasons. From each experimental plot, fruit diameter (mm), fruit length (mm), marketable fruit yield (kg/m^2), and total fruit yield of tomato (kg/m^2) were measured. Fruit diameter and length were measured by digital caliper and recorded as mm.

Total soluble solids (TSS) and pH levels of tomato juice were measured from a sample of 5 fruits/experimental plot/treatment as indicators for the quality of tomato fruits. The TSS values were determined using a Japanese-made hand refractometer (ATAGO model N-50E). Tomato pH values were measured with a hand-held pH meter (HI 3220 Ph/ORP Meter, Hanna Instruments, Inc. USA).

2.6 Benefit–Cost Analysis

Production cost of tomato for each treatment was calculated by totaling the cost of each weed control treatment (herbicides and hand hoeing). A fixed value of \$1197.27 ha^{-1} was added to the cost of weed control treatment to account for all other cultural practice costs required for tomato production, land preparation, seedling transplanting, fertilization, irrigation, transportation, harvesting, and general expenses (EAS 2019/2020). The cost of commercial products of Pend and Met herbicides was calculated according to their price in local pesticide shops during 2019 to 2021 (Table 10). Hand hoeing was done twice at 20 and 40 DAT which needed 20 person/day ha^{-1} and acquired 297.60\$ as the wages of 7.4\$/person/day. Gross return from each weed control treatment was calculated using the following equation (Daramola et al. 2020): gross return = tomato fruit yield (kg ha^{-1}) × market price of tomato fruit (1 kg = 0.247 \$). The net return from each treatment was calculated using the following equation: net return = gross return – cost of production (Daramola et al. 2021). Benefit–cost ratio for each treatment was calculated as the following equation: benefit–cost ratio = gross return ÷ cost of production (Daramola et al. 2021).

2.7 Statistical Analysis

The experiments were organized in a strip plot with three replications for each treatment. All data were statistically analyzed using ANOVA by CoStat 6.303 software, and the means of treatments were separated by the LSD test. The data of fresh biomass of weeds were logarithmic transformed (log[X + 1]) before analysis (Dey and Pandit 2020), to normalize their distribution. The interaction between treatments and seasons for all studied variables were insignificant except for weed data of *Beta vulgaris* at 42 DAT and *Rumex dentatus* at 98 DAT.

3 Results

3.1 Effect of Herbicides on Weed Density and Fresh Weight

Different annual weeds were encountered in the tomato experimental fields. Broad-leaved weeds were more dominant than grass species. At 42 DAT, the grass species *Dinebra retroflexa* (Vahl.) panz and *Echinochloa colonum* (L.) Link. were dominant (Table 1). The major annual broad-leaved were *Beta vulgaris* L., *Cichorium pumilum* Jacq., *Chenopodium murale* L., and *Portulaca oleracea* L., whereas *Ammi majus* was found only at 98 DAT (Table 2). Maximum annual weed density and weeds FW were observed in the un-weeded control in both seasons (Tables 2 and 3).

At 42 DAT in both seasons, all treatments significantly reduced FW of the individual and total grasses, total broad-leaved weeds, and total all weeds compared to the un-weeded control, while at 98 DAT, weed control efficacy by the different treatments was less marked (Tables 3 and 4).

As regard to grass weed control, all studied herbicides and hand hoeing resulted in 100% FW reduction of

Table 1 Effect of post-plant metribuzin (Sencor), different pre-plant pendimethalin products (Mostmicro, Respect, and Stop), hand hoeing, and un-weeded control on fresh weight (FW, g m^{-2}) of annual weeds in transplant tomato after 42 days after transplanting (DAT) in 2019/2020 (SI) and in 2020/2021 (SII)

	Weed species											
	B. vulgaris	*C. pumilum*	*C. murale*	*H. trionum*	*P. oleraceus*	*R. dentatus*	*S. oleraceus*	T. broad leaves	*E. colonium*	*D. retroflexa*	Total grass	Total all weeds
Treatments	SI											
	FW (g m^{-2})											
Sencor 70%	11.71 ± 8.03c †	15.10 ± 14.12a	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	49.06 ± 32.07ab	75.87 ± 25.64b	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	75.87 ± 25.64b
Mostmicro 36.5%	1.04 ± 0.68 cd	46.82 ± 25.79a	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	2.67 ± 2.67ab	50.53 ± 24.23b	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	50.53 ± 24.23b
Respect 45%	0.00 ± 0.00d	67.46 ± 47.61a	0.00 ± 0.00b	10.42 ± 7.64ab	0.00 ± 0.00b	0.20 ± 0.20b	0.00 ± 0.00b	78.08 ± 44.54b	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	78.08 ± 44.54b
Stop 45%	0.21 ± 0.21d	42.17 ± 23.20a	0.00 ± 0.00b	0.00 ± 0.00b	27.87 ± 22.87ab	5.38 ± 5.38ab	1.44 ± 1.44ab	77.07 ± 15.50b	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	77.07 ± 15.50b
Hand hoeing	49.03 ± 14.22b	115.91 ± 58.73a	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	13.97 ± 10.55ab	178.91 ± 70.74b	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	178.91 ± 70.74b
Control	1696.67 ± 392a	396.67 ± 114.7a	543.33 ± 284.3a	74.56 ± 41.57a	272.93 ± 171.8a	44.83 ± 23.34a	211.43 ± 134.1a	3240.41 ± 326.6a	33.03 ± 20.3a	34.23 ± 17.1a	67.26 ± 35.60a	3307.68 ± 327.6a
Weed density m^{-2}	14.67 ± 4.06a ‡	16.67 ± 1.33a	6.00 ± 3.47b	1.33 ± 0.67b	19.33 ± 3.53a	4.00 ± 2.00b	3.33 ± 1.76b	65.33 ± 4.81	3.33 ± 1.76b	6.00 ± 3.06b	9.33 ± 4.67	74.67 ± 9.40
Treatments	SII											
	FW (g m^{-2})											
Sencor 70%	22.22 ± 11.65ab	12.02 ± 7.79bc	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00a	26.83 ± 15.04ab	61.07 ± 18.82b	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	61.07 ± 18.84b
Mostmicro 36.5%	0.29 ± 0.29b	50.23 ± 14.90ab	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00a	0.00 ± 0.00b	50.52 ± 15.06b	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	50.52 ± 15.08b
Respect 45%	1.38 ± 1.38b	55.15 ± 53.98bc	12.20 ± 12.20b	13.22 ± 13.22b	10.07 ± 10.07b	0.71 ± 0.71a	0.28 ± 0.28b	93.02 ± 55.11b	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	93.02 ± 55.18b
Stop 45%	15.41 ± 4.64ab	0.00 ± 0.00c	0.00 ± 0.00b	0.00 ± 0.00b	10.96 ± 10.96b	0.00 ± 0.00a	0.36 ± 0.36b	26.73 ± 10.46b	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	26.73 ± 10.48b
Hand hoeing	0.91 ± 0.91b	87.11 ± 42.41ab	0.00 ± 0.00b	3.32 ± 3.32b	0.00 ± 0.00b	0.00 ± 0.00a	37.25 ± 7.28a	128.59 ± 31.22b	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	128.59 ± 31.26b
Control	520.00 ± 289.4a	706.67 ± 149.5a	1293.33 ± 247.4a	61.95 ± 15.20a	980.00 ± 326.6a	32.95 ± 32.95a	99.11 ± 52.09a	3694.01 ± 376.0a	5.23 ± 5.23a	49.70 ± 37.1a	54.93 ± 42.25a	3748.94 ± 376.5a
Weed density m^{-2}	4.67 ± 2.40b	26.67 ± 7.69ab	26.67 ± 10.91ab	4.00 ± 0.00b	40.00 ± 12.87a	3.33 ± 3.33b	3.33 ± 1.76b	108.67 ± 23.39	8.00 ± 8.00b	13.33 ± 8.82b	21.33 ± 16.59	130.00 ± 13.86
ANOVA¶												
Season	0.472 ns	0.269 ns	0.711 ns	0.076 ns	0.624 ns	0.186 ns	0.0004 ns	0.069 ns	0.124 ns	2.77 ns	0.005 ns	0.071 ns
Treatment	4.77**	3.40**	6.13**	2.34**	4.95**	0.815*	2.57**	3.36**	0.575**	1.35**	1.60**	3.38**
Treatment*season	1.47 *	0.493 ns	0.345 ns	0.088 ns	0.399 ns	0.108 ns	0.221 ns	0.067 ns	0.124 ns	2.77 ns	0.005 ns	0.066 ns

Mean ± SE within each column (†for FW of weeds) and a row (‡for weed density) having the same letter are not significantly different (LSD at 0.05 probability level); FW of weed data was logarithmically transformed (log[X + 1]) before statistical analysis; ¶, analysis of variance; ns, non-significant; * and **, significant; SE, standard error; FW, fresh weight of weeds; DAT, days after transplanting

Table 2 Effect of post-plant metribuzin (Sencor), different pre-plant pendimethalin products (Mostmicro, Respect, and Stop), hand hoeing, and un-weeded control and their interaction on fresh weight (FW, g m^{-2}) of annual weeds in transplant tomato after 98 DAT in 2019/2020 (SI) and in 2020/2021 (SII)

	Weed species						
	B. vulgaris	*C. pumilum*	*C. murale*	*R. dentatus*	*S. oleraceus*	*A. majus*	Total all weeds
Treatments	SI						
	FW (g m^{-2})						
Sencor 70%	346.89 ± 113.26ab	88.19 ± 49.52bc	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	39.08 ± 31.59c	474.16 ± 148.69 cd
Mostmicro 36.5%	113.09 ± 70.62b	703.33 ± 104.14ab	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	318.79 ± 186.08ab	1135.22 ± 51.14b
Respect 45%	197.11 ± 171.88b	14.17 ± 1.54c	0.00 ± 0.00b	0.00 ± 0.00b	7.41 ± 3.98b	201.88 ± 179.35bc	420.57 ± 154.46d
Stop 45%	211.61 ± 44.84b	84.61 ± 42.51bc	0.00 ± 0.00b	0.00 ± 0.00b	11.33 ± 11.33b	550.91 ± 85.33a	858.45 ± 93.23bc
Hand hoeing	468.04 ± 110.16ab	275.13 ± 107.64abc	0.00 ± 0.00b	0.00 ± 0.00b	13.09 ± 13.09b	0.00 ± 0.00d	756.25 ± 101.77bc
Control	4730.00 ± 446.44a	1856.67 ± 340.71a	3743.33 ± 1205.0a	318.85 ± 164.11a	2406.57 ± 968.57a	1323.48 ± 774.33a	14,378.90 ± 651.9a
Weed density m^{-2}	18.00 ± 1.15a	18.67 ± 3.71a	10.67 ± 4.81a	9.33 ± 2.40a	8.67 ± 1.33a	22.00 ± 14.05a	87.33 ± 18.34
Treatments	SII						
	FW (g m^{-2})						
Sencor 70%	322.20 ± 36.14b	29.45 ± 29.45 cd	0.00 ± 0.00b	19.07 ± 19.07b	0.00 ± 0.00c	41.77 ± 39.58b	412.50 ± 10.52c
Mostmicro 36.5%	69.15 ± 11.23bc	116.83 ± 42.44ab	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00c	390.00 ± 55.08a	575.97 ± 47.02bc
Respect 45%	88.15 ± 77.02c	208.68 ± 176.70bc	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00c	244.11 ± 68.44b	540.94 ± 162.47c
Stop 45%	231.31 ± 95.83bc	0.00 ± 0.00d	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00c	576.67 ± 118.37a	807.98 ± 210.75c
Hand hoeing	241.55 ± 32.14b	457.87 ± 125.34ab	0.00 ± 0.00b	0.00 ± 0.00b	55.25 ± 28.30b	97.37 ± 91.62b	852.05 ± 200.46b
Control	5963.33 ± 2070.78a	1739.09 ± 615.87a	5083.33 ± 920.92a	283.81 ± 283.81a	1573.33 ± 554.40a	739.96 ± 72.43a	15,382.85 ± 2465.91a
Weed density m^{-2}	15.33 ± 4.67ab	23.33 ± 1.76a	12.00 ± 1.15b	5.33 ± 5.33ab	8.00 ± 2.00b	14.67 ± 1.76ab	78.67 ± 4.81
ANOVA¶							
Season	0.026 ns	1.55 ns	0.0081 ns	0.012 ns	0.026 ns	0.81 ns	0.005 ns
Treatment	3.67**	5.77**	12.98**	1.83**	9.02**	5.48**	2.03**
Treatment*season	0.125 ns	0.733 ns	0.0081 ns	0.297 ns	0.564 ns	0.401 ns	0.034 ns

Mean ± SE within each column (†for FW of weeds) and a row (‡for weed density) having the same letter are not significantly different (LSD at 0.05 probability level); FW of weed data was logarithmically transformed (log[X + 1]) before statistical analysis; ¶ANOVA, analysis of variance; ns, non-significant; * and **, significant; SE, standard error; FW, fresh weight of weeds; DAT, days after transplanting

D. retroflexa and *E. colonum* at 42 DAT in both seasons (Table 4). Met (Sencor) and Pend (Mostmicro) generally reduced FW of broad-leaved weeds by 92–100% at 42 and 98 DAT in both seasons (Tables 3 and 4). However, Sencor exhibited an intermediate control of *S. oleraceus*. On the other hand, Mostmicro displayed an intermediate control of *C. pumilum* and *A. majus* (Tables 3 and 4).

As regard to different broad-leaved weeds, Respect reduced their FW by 78.66–100% at 42 DAT and by 67.01–100% at 98 DAT, in both seasons (Tables 3 and 4). In both seasons, Stop reduced broad-leaved FW by 88–100% at 42 DAT and by 95.44–100% at 98 DAT, while it showed lower control of *A. majus* at 98 DAT (Tables 3 and 4). Hand hoeing reduced broad-leaved weeds FW by 93.39–100% at 42 DAT (except for 70.78–87.67% in *C. pumilum*), while at 98 DAT, FW was reduced by 86.84–100% at 98 DAT, except for 73.67–85.18% in *C. pumilum* (Tables 3 and 4).

Met (Sencor), Mostmicro, Stop, and Respect resulted in a significant reduction of total all weeds FW by > 97% at 42 DAT in both seasons. At 98 DAT, FW was reduced by > 92% for Sencor and Mostmicro and by > 94% for Stop and Respect in both seasons (Tables 3 and 4). Hand hoeing resulted in FW reduction of total all weeds by > 94% at 6 and 98 DAT in both seasons (Tables 3 and 4).

3.2 Effect of Herbicides on Tomato Plant Stand Loss Rate

Hand hoeing did not cause any plant stand loss in both seasons (Fig. 2). Sencor showed the lowest rates for plant stand loss in both seasons (~ 9.3% and 9.3% at 42 DAT and 9.30 and 11.1% at 98 DAT, respectively). Pre-plant Pend products caused higher rates of plant stand loss than those recorded with other herbicides or un-weeded control treatment (Fig. 2a, 2b). At 42 DAT of the first and second seasons, Mostmicro, Stop, and Respect (pre-plant Pend products) resulted in plant stand loss rates of 31.5–33.3%, 38.9–51.9%, and 27.7–57.4%, respectively, which was increased at 98 DAT to 44.4%, 66.7–70.4%, and 69.4–75.0%, respectively (Fig. 2a, 2b). In the control plants, no plant stand loss was recorded at 42 DAT in both seasons, but increased to 54.5–61.7% at 98 DAT (Fig. 2a, 2b).

Table 3 Effect of post-plant metribuzin (Sencor), different pre-plant pendimethalin products (Mostmicro, Respect, and Stop), hand hoeing, and un-weeded control on weed control efficacy (%) on percent reduction in fresh weight of annual weeds in transplant tomato after 98 DAT in 2019/2020 (SI) and in 2020/2021 (SII)

	Weed species						
	B. vulgaris	*C. pumilum*	*C. murale*	*R. dentatus*	*S. oleraceus*	*A. majus*	Total all weeds
Treatments	SI						
	Weed control efficacy (%)						
Sencor 70%	92.67 ± 2.08ab	95.25 ± 2.41ab	100.00 ± 0.00†	100.00 ± 0.00†	100.00 ± 0.00a	97.05 ± 5.37ab	96.70 ± 1.02ab
Mostmicro 36.5%	97.61 ± 1.53a	62.12 ± 14.46c	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00a	75.91 ± 32.76bc	92.10 ± 0.62d
Respect 45%	95.83 ± 3.72ab	99.24 ± 0.22a	100.00 ± 0.00	100.00 ± 0.00	99.69 ± 0.48a	84.75 ± 29.69ab	97.08 ± 1.01a
Stop 45%	95.53 ± 1.15ab	95.44 ± 2.12ab	100.00 ± 0.00	100.00 ± 0.00	99.53 ± 0.39a	58.37 ± 22.66c	94.03 ± 0.85 cd
Hand hoeing	90.10 ± 1.35b	85.18 ± 5.97b	100.00 ± 0.00	100.00 ± 0.00	99.46 ± 2.47a	100.00 ± 0.00a	94.74 ± 0.51bc
Control	–	–	–	–	–	–	–
Weed density m^{-2}	20.61 ± 1.32a	21.37 ± 4.25a	12.21 ± 5.51a	10.69 ± 2.75a	9.92 ± 1.53a	25.19 ± 16.09a	100.00 ± 21.00
C.V. (%)	4.21	8.35	–†	–	0.587	15.03	1.22
Treatments	SII						
	Weed control efficacy (%)						
Sencor 70%	94.60 ± 3.39b	98.31 ± 1.09a	100.00 ± 0.00†	93.28 ± 2.24a	100.00 ± 0.00a	94.35 ± 6.67a	97.32 ± 0.44a
Mostmicro 36.5%	98.84 ± 0.56a	93.28 ± 1.06a	100.00 ± 0.00	100.00 ± 0.00a	100.00 ± 0.00a	47.29 ± 13.13bc	96.26 ± 0.30a
Respect 45%	98.52 ± 0.91a	88.00 ± 6.39ab	100.00 ± 0.00	100.00 ± 0.00a	100.00 ± 0.00a	67.01 ± 0.17ab	96.48 ± 1.54a
Stop 45%	96.12 ± 2.20ab	100.00 ± 0.00a	100.00 ± 0.00	100.00 ± 0.00a	100.00 ± 0.00a	22.07 ± 9.37c	94.75 ± 0.87a
Hand hoeing	95.95 ± 2.55ab	73.67 ± 9.58b	100.00 ± 0.00	100.00 ± 0.00a	96.49 ± 7.14b	86.84 ± 11.03a	94.46 ± 0.38a
Control	–	–	–	–	–	–	–
Weed density m^{-2}	19.49 ± 5.93ab	29.66 ± 2.24a	15.25 ± 1.47b	6.78 ± 6.78b	10.17 ± 2.54b	18.64 ± 2.24ab	100.00 ± 6.11
C.V. (%)	1.80	10.41	–	5.28	1.40	30.02	1.84

Means ± SE. SE, standard error. Weed control efficacy (%) = [(FW of weed in control plot − FW of weed in treated plot) ÷ FW of weed in control plot] × 100, that reflects percent reduction in FW of weeds; †, Not calculated; C.V. (%), coefficient of variation

3.3 Effect of Herbicides on Tomato Growth Characteristics

Tomato growth characteristics, including number of branches per plant, stem diameter (mm), shoot fresh weight (g), and shoot dry weight (g), were significantly influenced by the elimination of weed competition caused by all the studied herbicides as compared to the un-weeded control treatment in both seasons (Table 5). The highest significant increases of branch number, plant height, stem diameter, and shoot FW were observed in plots where weeds were treated with Sencor and Mostmicro in both seasons, whereas un-weeded control treatment showed the lowest levels (Table 5). Leaf chlorophyll concentrations were significantly improved in plots in which all the different studied herbicides were applied, as compared to the un-weeded control plots (Table 5) without significant differences among the different herbicides (Table 5). A coefficient of determination of 99.9% shows that the data of the relationship between SPAD units and chlorophyll concentrations fit the regression model (Table 5).

3.4 Effect of Herbicides on Tomato Fruit Yield and Yield Attributes

Fruit diameter and fruit length were significantly increased in all plots in which weeds were treated with tested herbicides and hand hoeing treatments in both seasons (except Stop in the first season), compared to the un-weeded control (Table 6). The highest significant increases in fruit diameter and length were recorded in plots in which weeds were treated with Mostmicro and Sencor in both seasons (Table 6). In the two seasons, plots in which weeds were treated with Sencor had the highest marketable and total fruit yields of 1.99–2.17 kg/m^2 and 2.236–2.433 kg/m^2, respectively, followed by Mostmicro (1.37–1.43 kg/m^2 and 1.45–1.57 kg/m^2, respectively) and hand hoeing (1.01–1.36 ton ha^{-1} and 1.22–1.58 kg/m^2, respectively) (Table 6). In both seasons, the lowest marketable fruit yields (0.05–0.09 ton ha^{-1}) and total fruit yield (0.07–0.09 ton ha^{-1}) were recorded in plots of the un-weeded control treatment (Table 8). No significant differences were observed among the different herbicide-treated plots regarding

Table 4 Effect of post-plant metribuzin (Sencor), different pre-plant pendimethalin products (Mostmicro, Respect, and Stop), hand hoeing, and un-weeded control on weed control efficacy (%) on percent reduction in fresh weight of annual weeds in transplant tomato after 42 DAT in 2019/2020 (SI) and in 2020/2021 (SII)

	Weed species											
	B. vulgaris	*C. pumilum*	*C. murale*	*H. trionum*	*P. oleraceus*	*R. dentatus*	*S. oleraceus*	T. broad leaves	*E. colonium*	*D. retroflexa*	Total grass	Total all weed
Treatments	SI											
	Weed control efficacy (%)											
Sencor 70%	99.31 ± 0.47a†	96.19 ± 3.56a	100.00 ± 0.00	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	76.80 ± 15.17a	97.66 ± 1.10a	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	97.71 ± 0.78a
Mostmicro 36.5%	99.94 ± 0.04a	88.20 ± 6.50a	100.00 ± 0.00	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	98.74 ± 1.26a	98.44 ± 1.04a	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	98.47 ± 0.73a
Respect 45%	100.00 ± 0.00a	82.99 ± 12.0a	100.00 ± 0.00	86.02 ± 10.24a	100.00 ± 0.00a	99.55 ± 0.450a	100.00 ± 0.00a	97.59 ± 1.90a	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	97.64 ± 1.35a
Stop 45%	99.99 ± 0.01a	89.37 ± 5.85a	100.00 ± 0.00	100.00 ± 0.00a	89.79 ± 10.21a	88.00 ± 12.00a	99.32 ± 0.68a	97.62 ± 0.66a	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	97.67 ± 0.47a
Hand hoeing	97.11 ± 0.84b	70.78 ± 14.81a	100.00 ± 0.00	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	93.39 ± 4.99a	94.48 ± 3.02a	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	94.59 ± 2.14a
Control	–	–	–	–	–	–	–	–	–	–	–	–
Weed density m^{-2}	19.64 ± 5.43a‡	22.32 ± 1.79a	8.04 ± 4.64b	1.79 ± 0.89b	25.89 ± 4.72a	5.36 ± 2.68b	4.46 ± 2.36b	87.50 ± 6.44	4.46 ± 2.36b	8.04 ± 4.09b	12.50 ± 6.25	100.00 ± 12.60
C.V. (%)	0.671	21.41	–	8.16	8.07	9.58	13.55	3.54	–	–	–	2.48
Treatments	SII											
	Weed control efficacy (%)											
Sencor 70%	95.73 ± 3.88b	98.30 ± 1.91a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	72.93 ± 26.28bc	98.35 ± 0.88a	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	98.37 ± 0.87a
Mostmicro 36.5%	99.94 ± 0.10a	92.89 ± 3.65a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	98.63 ± 0.71a	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	98.65 ± 0.70a
Respect 45%	99.73 ± 0.46a	92.20 ± 13.23a	99.06 ± 1.63a	78.66 ± 36.96a	98.97 ± 1.78a	97.84 ± 3.75a	99.72 ± 0.49ab	97.48 ± 2.58a	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	97.52 ± 2.55a
Stop 45%	97.04 ± 1.54ab	100.00 ± 0.00a	100.00 ± 0.00a	100.00 ± 0.00a	98.88 ± 1.94a	100.00 ± 0.00a	99.64 ± 0.63ab	99.28 ± 0.49a	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	99.29 ± 0.48a
Hand hoeing	99.83 ± 0.30a	87.67 ± 10.39a	100.00 ± 0.00a	94.64 ± 9.28a	100.00 ± 0.00a	100.00 ± 0.00a	62.41 ± 12.72c	96.52 ± 1.46a	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00	96.57 ± 1.44a
Control	–	–	–	–	–	–	–	–	–	–	–	–
Weed density m^{-2}	3.59 ± 1.85bc	20.51 ± 5.91ab	20.51 ± 5.91ab	3.08 ± 0.00bc	30.77 ± 9.89a	2.56 ± 2.56c	2.56 ± 1.36c	83.59 ± 17.89	6.15 ± 6.15bc	10.26 ± 6.78bc	16.41 ± 12.76	100.00 ± 10.89
C.V. (%)	1.85	9.01	0.732	18.53	1.02	1.68	16.43	1.60	–	–	–	1.58

Weed control efficacy (%) = [(FW of weed in control plot − FW of weed in treated plot) ÷ FW of weed in control plot] × 100, that reflects percent reduction in FW of weeds; mean ± SE within each column (†for FW of weeds) and a row (‡for weed density) having the same letter are not significantly different (LSD at 0.05 probability level); C.V. (%), coefficient of variation. SE, standard error; FW, fresh weight of weeds; DAT, days after transplanting

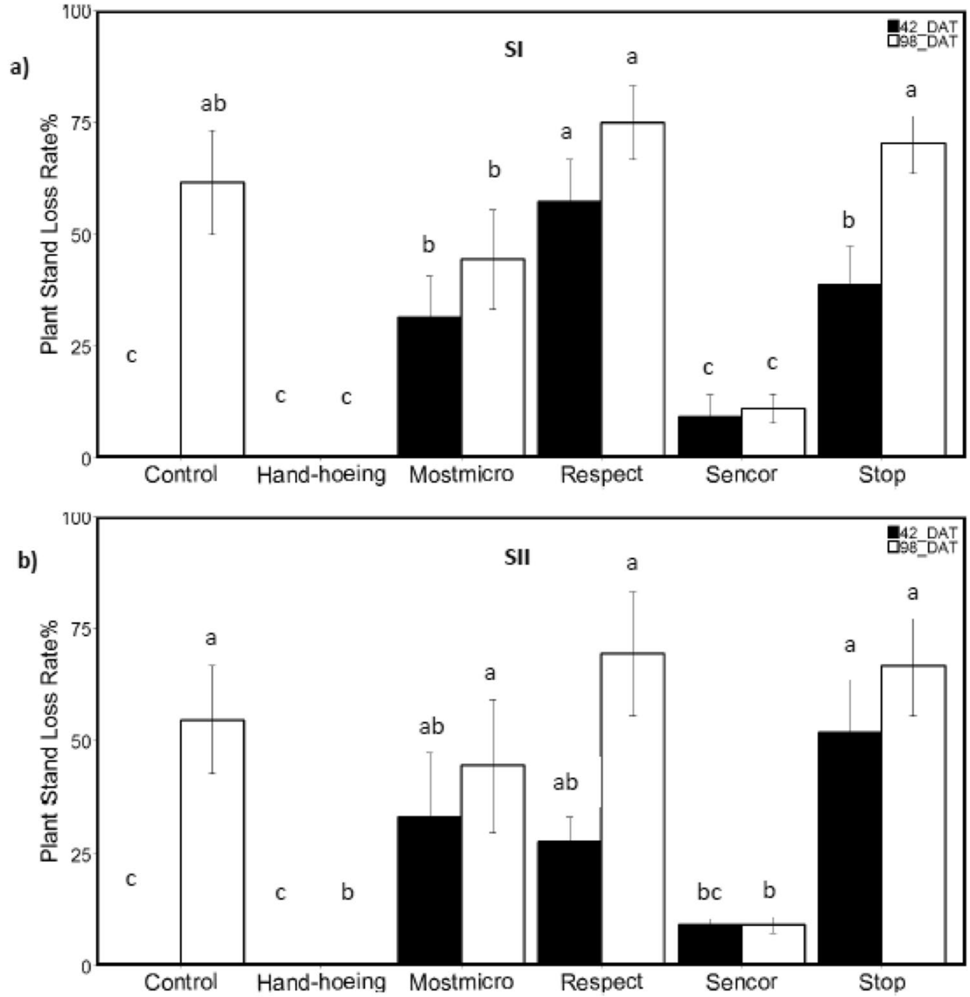

Fig. 2 Effect of grass foliar application with different herbicides on plant stand loss rate at 42 DAT and at 98 DAT of tomato (*Solanum lycopersicum* L.) plants grown during 2019/2020 (SI) and 2020/2021 (SII) seasons. Plant stand loss rate was 0.0% for the control at 42 DAT and in hand hoeing at 42 DAT and at 98 DAT in the two seasons. Data are means ± SE. SE, standard error. Differences between mean values followed by the same letter in each column are not significant using the least significant difference (LSD) test at $p \leq 0.05$. DAT, days after transplanting

tomato pH (Table 6). Likewise, fruit TSS was not significantly different among the un-weeded control plots and the plots of the different herbicide treatments except for Stop treatment in the first season and Respect in the second season (Table 6).

3.5 Benefit–Cost Analysis

Met followed by Pend products had the lowest cost of production, but hand hoeing had the highest total cost value (Table 7). All weed control treatments resulted in higher cost of production, gross return, and benefit–cost ratio than the un-weeded control (Table 7). Met resulted in the highest gross return (6002.10 and 5532.80 \$ ha^{-1}), net return (4749.74 and 4280.44 \$ ha^{-1}), and benefit–cost ratio (4.79 and 4.42) in the first and second seasons, respectively, followed by Mostmicro and hand hoeing (Table 7). Respect and Stop treatments resulted in the lowest gross and net returns and benefit–cost ratio than other weed control treatments (Table 7).

4 Discussion

Weeds are one of the most offensive and wieldy spread agricultural pests that threaten global food security and cost billions of dollars each year because of their harm to crops (Chen et al. 2021; Sherwani et al. 2015). Tomatoes are very sensitive to weed competition, particularly at the early stages after transplantation (Mennan et al. 2020) with serious effects on tomato growth, development, and flowering leading to a great loss of yield quantity and quality (Mennan et al. 2020; Olayinka et al. 2017).

The present experiment showed that application of three pre-plant Pend products (Mostmicro, Respect, and Stop) and a post-plant Met herbicide (Sencor) were more efficient than hand hoeing in weed control. All tested herbicides and hand hoeing significantly reduced FW of annual monocot and dicot weeds by > 94% at 42 DAT and by > 92% at 98 DAT compared to the un-weeded control treatment. Met is a synthetic organic compound that is used as a selective triazinone herbicide to control weeds in tomato and other crops (Samir et al. 2020). Pend is

Table 5 Effect of grass foliar application of different herbicides on growth characteristics, leaf relative chlorophyll content (SPAD value), and leaf chlorophyll concentration (Chl conc.) of *Solanum lycopersicum* L. plants grown during 2019/2020 (SI) and 2020/2021(SII) seasons

Treatments		No. of branches per plant^{-1}	Plant height (cm)	Stem diameter (mm)	Shoot FW (g)	Shoot DW (g)	SPAD value	Chl conc. †
SI								
Control		3.6 ± 0.9 c	65.4 ± 2.9 c	9.5 ± 0.2 c	25.0 ± 4.8 d	4.6 ± 0.4 d	36.89 ± 1.21b	0.93 ± 0.08b
Hand hoeing		9.2 ± 0.2 ab	76.9 ± 4.4 abc	14.3 ± 0.6 b	170.6 ± 18.4 c	39.4 ± 2.0 c	54.13 ± 1.41a	2.05 ± 0.09a
Mostmicro		9.7 ± 0.5 a	86.6 ± 2.1 a	19.9 ± 0.7 a	301.1 ± 15.6 a	67.8 ± 2.0 a	53.68 ± 2.63a	2.02 ± 0.17a
Respect		7.6 ± 0.6 b	68.9 ± 6.5 c	15.0 ± 1.0 b	173.8 ± 4.1 c	56.7 ± 1.0 b	54.44 ± 1.01a	2.07 ± 0.07a
Sencor		10.2 ± 0.2 a	82.0 ± 3.9 ab	20.9 ± 1.2 a	247.2 ± 17.1 b	56.1 ± 3.9 b	54.53 ± 0.47a	2.07 ± 0.03a
Stop		8.4 ± 0.6 ab	72.3 ± 2.7 bc	15.0 ± 0.2 b	168.6 ± 14.3 c	47.8 ± 5.5 bc	55.20 ± 0.76a	2.12 ± 0.05a
SII								
Control		2.4 ± 0.06 d	66.1 ± 2.2 c	8.4 ± 0.8 c	19.4 ± 3.5 d	3.6 ± 0.3 c	36.96 ± 0.73b	0.94 ± 0.05b
Hand hoeing		8.9 ± 0.3 bc	69.7 ± 1.5 c	15.2 ± 0.5 b	154.4 ± 16.8 c	37.8 ± 4.5 b	54.75 ± 0.32a	2.09 ± 0.02a
Mostmicro		9.3 ± 0.2 b	84.9 ± 1.8 a	19.9 ± 1.4 a	296.9 ± 12.2 a	62.2 ± 4.8 a	54.91 ± 1.25a	2.10 ± 0.08a
Respect		8.3 ± 0.0 c	78.1 ± 2.8 b	15.0 ± 0.3 b	200.8 ± 5.3 bc	59.2 ± 1.4 a	53.53 ± 2.21a	2.01 ± 0.14a
Sencor		11.0 ± 0.5 a	81.6 ± 2.0 ab	17.1 ± 0.5 b	240.6 ± 21.0 b	53.9 ± 3.1 a	53.91 ± 1.70a	2.03 ± 0.11a
Stop		8.2 ± 0.4 c	77.4 ± 1.4 b	15.8 ± 0.7 b	174.7 ± 19.7 c	53.3 ± 7.3 a	55.79 ± 0.13a	2.16 ± 0.01a
ANOVA	DF	Mean square	Mean square	Mean square	Mean square	Mean square	Mean square	Mean square
Season	1	0.111 ^{ns}	8.12 ns	2.56 ns	0.08 ns	1.40 ns	0.238 ^{ns}	0.0009 ^{ns}
Treatment	5	42.75***	297.86***	91.27***	52,281.16***	2892.02***	310.12**	1.299**
Treatment*season	5	0.823 ^{ns}	48.16 ^{ns}	4.73 ns	336.56 ns	22.92 ^{ns}	0.991 ^{ns}	0.004 ^{ns}
Regression equation							$y = -1.482 + 0.0660*x$	$y = -1.417 + 0.0630*x$
R^2							0.999	0.999

Means ± SE. SE, standard error. Differences between mean values followed by the same letter in each column are not significant by the least significant difference (LSD) test at $p \leq 0.05$; ns, non-significant; ***highly significant, ** significant difference (p˂0.05). FW, fresh weight; DW, dry weight; † Chl conc., chlorophyll concentration that is calculated from SPAD value using a liner model $y = 0.0647x - 1.4543$

a dinitroaniline herbicide, used globally to control most annual grasses and many annual broad-leaved weeds in crop fields such as tomato (Lin et al. 2007).

Pend products control seedlings of annual weeds by inhibiting the growth and development of root and shoot of susceptible weeds (Parka and Soper 1977) providing excellent annual weed management in vegetable crops such as tomato (Lin et al. 2007; Qasem 1998). The efficacy of Met as a weed control treatment is attributed to its interrupted effects on the photosynthetic systems of weeds by inhibiting photosystem II (PSII) electron transport (Senseman 2007), but still can elicit injury to tomato (Chaudhari et al. 2017). Similar to our results, pre-emergence application of Pend achieved high activity against numerous narrow and broad leaf weeds in tomato (Olayinka et al. 2017; Pala and Karİpçİn 2021; Qasem 1998). Also, post-plant application of Met at 210 g ha^{-1} elicited high control efficacy (84–100%) against monocot and dicot weed species in the Solanaceae family including tomato (Wilson et al. 2001).

Although all tested herbicides in the present study exhibited high efficiency in the weed control, they also caused variable rates of tomato stand loss. Tomato plants showed higher tolerance to post-plant application of Met (Sencor) as indicated by its lower rates for plant stand loss as compared to Pend or control treatments. This can be explained as Met is usually rapidly metabolized before injury occurs. It has been reported that about 80% of the absorbed Met is metabolized to non-toxic substrate in tolerant tomato seedlings within a day of treatment (Frear et al. 1983), and the resulting crop injury is transient (McNaughton 2013). However, this depends on the cultivars used (McNaughton 2013). In harmony with the findings from our experiment, using Met (280 g ha^{-1}) was also concomitant with minimal injury of tomato plants at 3 weeks after transplantation (Chaudhari et al. 2015).

Unlike Met, all studied Pend products (Mostmicro, Stop, and Respect) resulted in significantly higher rates of stand loss than those observed with hand hoeing and Sencor treatments at 98 DAT. To the best of our knowledge, there is no available information in the literature regarding the effects of "Mostmicro," "Stop," and "Respect" on tomato. In general, Pend can cause unintended negative consequences on crops as it inhibits root cell division; impedes root development, extension, and growth; and decreases the number of primary and lateral roots resulting in plant dehydration and lethality (Chen et al. 2021; Hammok and Al-mandeel 2020). In accordance to our findings, the lowest survival rates of field-grown tomato were reported when Pend was used alone (at

Table 6 Effect of grass foliar application with herbicides on fruit yield, its components, fruit pH, and TSS of *Solanum lycopersicum* L. plants grown during 2019/2020 (SI) and 2020/2021 (SII) seasons

Treatments		Fruit diameter (mm)	Fruit length (mm)	Marketable fruit yield Kg/m^2	Total fruit yield Kg/m^2	Fruit pH	Fruit TSS
SI							
Control		44.7 ± 1.8 c	39.8 ± 1.3 b	0.088 ± 0.039 c	0.092 ± 0.041 c	3.87 ± 0.02 a	4.84 ± 0.06 b
Hand hoeing		54.4 ± 1.7 ab	48.6 ± 1.3 a	1.357 ± 0.285 b	1.583 ± 0.224 b	3.84 ± 0.03 a	5.26 ± 0.15 ab
Mostmicro		57.3 ± 0.9 a	51.6 ± 0.4 a	1.434 ± 0.249 ab	1.571 ± 0.245 b	3.88 ± 0.04 a	5.31 ± 0.06 ab
Respect		52.6 ± 0.41 b	49.0 ± 1.0 a	0.411 ± 0.116 c	0.446 ± 0.134 c	3.83 ± 0.04 a	5.47 ± 0.08 ab
Sencor		56.2 ± 0.6 ab	50.0 ± 0.3 a	2.174 ± 0.427 a	2.433 ± 0.449 a	3.90 ± 0.06 a	5.43 ± 0.15 ab
Stop		48.0 ± 2.2 c	43.8 ± 2.5 b	0.294 ± 0.070 c	0.323 ± 0.078 c	3.86 ± 0.03 a	5.83 ± 0.44 a
SII							
Control		45.9 ± 1.6 b	37.9 ± 1.6 c	0.049 ± 0.013 d	0.071 ± 0.020 d	3.83 ± 0.00 a	5.03 ± 0.17 b
Hand hoeing		53.6 ± 1.4 a	47.6 ± 0.6 ab	1.008 ± 0.058 bc	1.216 ± 0.099 bc	3.84 ± 0.02 a	5.26 ± 0.20 ab
Mostmicro		56.0 ± 1.7 a	50.7 ± 0.7 a	1.372 ± 0.436 ab	1.449 ± 0.442 ab	3.88 ± 0.03 a	5.67 ± 0.21 ab
Respect		54.0 ± 2.6 a	50.2 ± 1.5 ab	0.532 ± 0.042 cd	0.602 ± 0.066 bcd	3.87 ± 0.02 a	6.03 ± 0.21 a
Sencor		56.6 ± 0.2 a	50.4 ± 0.2 ab	1.998 ± 0.256 a	2.236 ± 0.299 a	3.87 ± 0.07 a	5.60 ± 0.32 ab
Stop		52.9 ± 0.04 a	47.2 ± 0.7 b	0.496 ± 0.366 cd	0.544 ± 0.394 cd	3.87 ± 0.03 a	5.54 ± 0.24 ab
ANOVA	DF	Mean square	Mean square	Mean square	Mean square	Mean square	Mean square
Season	1	8.41 ^{ns}	0.40 ^{ns}	0.01 ^{ns}	0.03 ^{ns}	5.63e$^{-5\ ns}$	0.25 ns
Treatment	5	109.13***	123.9***	3.46***	4.29***	0.002 ^{ns}	0.54*
Treatment*season	5	7.66 ^{ns}	5.73 ^{ns}	0.05 ^{ns}	0.07 ^{ns}	0.001 ^{ns}	0.13 ns

Means ± SE. SE, standard error. Differences between mean values followed by the same letter in each column are not significant by the least significant difference (LSD) test at $p \leq 0.05$; ns, non-significant, ***highly significant. TSS, total soluble solids

Table 7 Effect of weed control methods on the cost of tomato production, fruit yield, gross return, net return, and benefit–cost ratio in tomato in 2019/2020(SI) and 2020/2021(SII)

Treatments	Weed control cost ($ ha^{-1})		Cost of production ($ ha^{-1}) † (a)		Yield (Kg ha^{-1})		Gross return ‡ ($ ha^{-1}) (b)		Net return ¶ ($ ha^{-1}) (b-a)		Benefit–cost ratio§ (b/a)	
	SI	SII	SI	SII	SI	SII	SI	SII	SI	SII	SI	SII
Control	0.00	0.00	1197.27	1197.27	920.0	710.0	227.24	175.37	− 970.03	− 1021.90	0.19	0.15
Hand hoeing	297.60	297.60	1494.90	1494.90	15,800.0	12,200.0	3902.60	3013.40	2407.73	1518.53	2.61	2.02
Mostmicro	70.51	70.51	1267.78	1267.78	15,700.0	14,500.0	3877.90	3581.50	2610.12	2313.72	3.06	2.83
Respect	69.05	69.05	1266.32	1266.32	4460.0	6020.0	1101.62	1486.94	− 164.70	220.62	0.87	1.17
Sencor	55.09	55.09	1252.36	1252.36	24,300.0	22,400.0	6002.10	5532.80	4749.74	4280.44	4.79	4.42
Stop	59.94	59.94	1257.21	1257.21	3230.0	5440.0	797.81	1343.68	− 459.40	86.47	0.63	1.07

† Average of 1.00 US $ = 16.22 E£ (Egyptian pound, Egyptian currency) in 2019/2020 to 2020/2021; ‡gross return = tomato fruit yield (kg ha^{-1}) × market price of tomato fruit (0.247 US dollar ($) kg^{-1} in both seasons); ¶ net return = gross return − cost of production; § benefit–cost ratio = gross return ÷ cost of production

2.01 or 3.01 ha^{-1} at 6 and 9 weeks after planting) compared to Pend combined with weeding or mulching, glyphosate (alone or combined with weeding or mulching), weeding alone, or mulching alone (Tetteh et al. 2011).

In the present study, all weed control plots showed significantly higher parameters of tomato vegetative growth (including the number of branches, stem diameter, plant height, and shoot FW and DW) as compared to the un-weeded control (except for plant height in hand hoeing). However, the highest significant increase in most vegetative parameters was found in Mostmicro and Sencor plots. Similar findings were previously reported in tomatoes treated with Met (Samant and Prusty 2014). Also, Olayinka et al. (2017) found that plant height, number of leaves, and leaf area of tomato were increased in plots treated with Pend herbicide (at 4 l ha^{-1}) as compared to the un-weeded control plants.

Beside the improved vegetative growth parameters, plots with weed control treatments also showed significantly higher tomato leaf chlorophyll concentration than the un-weeded control. The mode of action of Met is based on inhibition of the photosynthetic electron transport (Hill reaction) (Chaudhari et al. 2020; Rakitsky 2011; Volova et al. 2020). This inhibition leads to the production of reactive oxygen species (ROS) followed by loss of chlorophyll and other pigments, as a result of oxidation (Sherwani et al. 2015). This leads to collapse of cells and cell organelles and eventual whole plant death (Sherwani et al. 2015). However, the low stand loss rates observed in our Met plots, along with the preserved leaf chlorophyll and improved vegetative growth, signify that the used tomato hybrid is tolerant to Met. Similarly, Pend did not affect chlorophyll content since its primary mode of action (as in dinitroaniline herbicides) is inhibiting the cell division and targeting the microtubules that form plant cell wall (Sherwani et al. 2015).

In the present study, fruit diameter and length were significantly higher in plots treated with hand hoeing or herbicides (except for Stop in the first season) compared to the control. Met-treated plots gave the highest significant marketable and total fruit yield followed by Pend (Mostmicro) plots, but it was not significantly different from Met. Interestingly, although Mostmicro gave a 44% stand loss rate at 98 DAT, the survived plants gave high marketable and total fruit yield that is comparable to hand hoeing with its 0% stand loss rate. Despite the relatively high stand loss rate in Mostmicro plots, the better vegetative growth characteristics of those plants (compared to those treated with other herbicides or hand hoeing) have contributed to the improved marketable and total fruit yield.

Compared to hand hoeing, the improved growth, leaf chlorophyll concentration, and fruit yield in plots treated with Sencor and Mostmicro could be attributed to their efficiency in weed control and hence the lowered weed density and the reduced competition for main environmental resources, which improved photosynthetic efficiency and carbohydrate sinks (Olayinka et al. 2017; Zarzecka et al. 2020). In contrast, the unsatisfactory control for *S. oleraceus* and *C. pumilum* after 98 DAT in hand hoeing plots increased weed competitiveness with tomato plants, particularly at the early growth stages, leading to a decreased tomato yield. In agreement with our results, fruit yield was constantly high with Met alone or with rimsulfuron and rimsulfuron sequential treatments (Ackley et al. 2017). Also, Pend at 4 l ha^{-1} was associated with increased number of fruits and tomato fruits FW compared to the un-weeded control plants (Olayinka et al. 2017).

The benefit of improved tomato yield in the plots treated with Met or Mostmicro did not come at the cost of the fruit quality. Our study has shown that tomato fruit pH was comparable in all studied weed control treatments, which comes in agreement with observation reported by Olayinka et al. (2017). Similarly, fruit TSS in all studied weed control treatments was not significantly different from the un-weeded control, which parallels observations reported by Reddy et al. (2018).

In the present study, Stop and Respect herbicides gave lower marketable and total fruit yields than hand hoeing. This could be attributed to the higher sensitivity of our tomato hybrid to those particular products. The differential sensitivity of tomato transplants to the different Pend products can be affected by the application rate and/or the chemical and physical characteristics of adjuvants and other additives in Pend formulations (Zhang et al. 2018).

The lowest growth and yield characteristics in the current study were recorded in the un-weeded control plants as the increased weed density and height have directly impacted tomato plants with a 54.5–61.7% stand loss rate. The indirect impact of weeds on tomatoes is caused by creating a microclimate favorable to disease occurrence (Mendonça et al. 2021). In the two seasons of a study on tomatoes, Adigun et al. (2018) stated that the maximum yield reduction (59–76%) was recorded in the control plots, while the greatest yield was obtained after the application of butachlor herbicide and supplementary hand hoeing.

In this study, tomato fruits were manually harvested after 126 DAT which are less than the reported pre-harvest interval of Met (45 days) or Pend (55–60 days) in Egypt (APCE in 2021). Earlier studies have shown that residues of Met and Pend applied to tomato (at 0.5 and 1 kg ha^{-1}, respectively) were below the detectability limit in tomato fruits and in soil samples at the time of tomato harvest with maximum residue levels (MRLs) of 0.05 mg kg^{-1} (Saritha et al. 2017; Sondhia 2013). Thus, tomato plants treated with Met and Pend have been shown to be safe to human health in Egypt.

Regarding the treatment costs, our study showed that Met was the most cost-effective, being the cheapest treatment that was associated with the highest tomato yield, gross, net returns, and benefit–cost ratio. Mostmicro and hand hoeing were the second and third most cost-effective treatments after Met, respectively. Respect and Stop, however, had the highest impact on survival, growth, and yield, which resulted in the lowest gross revenues and benefit–cost ratios among the studied herbicides. Weed infestation in the control treatment led to the highest fruit yield losses causing immense financial losses. In harmony with our results, application of herbicides alone or plus hand weeding to tomato plots provided efficient weed control, which resulted in higher fruit yield and gross and net returns twice than that of hand weeding alone (Daramola et al. 2021).

5 Conclusions

Post-emergence Metribuzin (Sencor) or pre-emergence pendimethalin (Mostmicro, Respect, and Stop) and hand hoeing treatments are effective tools in reducing annual monocot and dicot weeds in tomato fields. All tested herbicides had variable rates of tomato stand loss. Tomato "hybrid 065,010" was more tolerant to Metribuzin (Sencor), with the lowest stand loss rates compared to all studied pendimethalin products. Metribuzin- and Mostmicro-treated plots had the best vegetative growth and yield, but the highest yield was observed in Metribuzin plots. Metribuzin was the most cost-effective weed control treatment in this study. More research on the use of Pend products of Mostmicro, Stop, and Respect is still needed to determine their efficacy in weed control with different tomato cultivars.

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Declarations

Conflicts of Interest The authors declare no competing interests.

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