INTEGRATIVE CONTROL OF BRANCHED BROOMRAPE (*Orobanche ramosa* L.) USING SOIL SOLARIZATION AND SOME CHEMICAL SUBSTANCES IMPROVES THE GROWTH AND YIELD OF TOMATO PLANTS

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ABSTRACT

Tomato cultivation in the Mediterranean region is susceptible to infestation by the parasitic weed branched broomrape (*Orobanche ramose* L.), and can lead to severe yield losses. Efficiency of individual soil solarization, soil disinfection technique that uses passive solar heating, or in integration with Gesaprim or H_3PO_4 to control *O. ramosa* and thus increase the growth and yield of tomatoes (Lojain 935 and GS-12 hybrids) under the conditions of fields experiments was studied over two growing summer seasons of 2018 and 2019. The survey of the distribution of *O. ramosa* in the provinces of Fayoum Governorate, which was implemented in 2016, showed that Ibshawai, Yusuf Al-Seddiq and Itsa provinces had the highest percentages of incidence and attack severity, while Tamyia and Fayoum provinces showed the lowest percentages. The highest infestations were detected in winter season, while fall season showed the lowest infestations. In the field experiments, soil solarization was the best single treatment compared to organic manures, H_3PO_4, NPK fertilizer, and Gesaprim in controlling *O. ramosa* and increasing the growth and yield parameters of tomato hybrids. Additionally, soil solarization integrated with Gesaprim or H_3PO_4 was the best integrative application for Lojain 935 hybrid followed by the same integrative application for GS-12 hybrid. This best integrative application conferred the percent minimal incidence and attack severity of *O. ramosa* and the highest growth parameters (fresh and dry weights of shoots) and yield components (fruits No. plant^{-1}, and fruits yield plant^{-1}) of both tomato hybrids with superiority of Lojain 935. Therefore, the results of this study recommend the use of this best integrative application [soil solarization integrated with Gesaprim or H_3PO_4] as an appropriate technique for tomato production where the risk of branched broomrape infestation is high.

Keywords: Tomato production, branched broomrape, parasitic weed, soil solarization, control, Gesaprim, H_3PO_4, organic manures, NPK fertilizer.

INTRODUCTION

As phytoparasitic weeds, broomrapes (*Orobanche* spp.) cause great destructive damages to several crops in Europe, the Mediterranean region, Central Asia, the Arabian Peninsula and North African countries (**Klein and Kroschel, 2002; Sauerborn, 2003**), including Egypt (**Kader-Abdel and -El Mougy, 2007**). The life cycle of most of the parasites occurs below-ground connected to the host plant. Therefore, it is very difficult to control them either through agronomic practices or herbicides (**Goldwasser *et al.*, 2003**). In addition, control is made difficult by the fact that each plant produces thousands of dust-like seeds of 0.2- to 0.3-mm-diameter that are readily distributed and remain viable in the soil for many years (**Goldwasser *et al.*, 2001**). Although a broad spectrum of control methods has been attempted (cultural, physical, chemical, and biological), no significant reduction of infes- tation has been achieved. Hence, other control methods are needed (**Klein and Kroschel, 2002**).

Among the *Orobanche* spp., branched broomrape (*Orobanche ramosa* L.) is one of the most prevalent and devastating. Together with Egyptian broomrape (*Orobanche aegyptiaca* Pers.), it infests about 2.6 million ha of solanaceous crops (predominately tobacco, potato, tomato, and eggplant), mainly in the Mediterranean basin, North Africa, and Asia (**Zehhar *et al.*, 2002; Boari *et al.*, 2003; Mauromicale *et al.*, 2005a, 2005b**). In certain parts of Greece, Lebanon, Jordan, and Egypt, branched broomrape frequently damage tomato, tobacco, potato, and faba bean fields, with yield losses of 100% in many cases (**Goldwasser *et al.*, 2001; Haidar *et al.*, 2003; Mauromicale *et al.*, 2005a, 2005b**). Other crops in the Mediterranean region commonly parasitized and severely influenced by branched broomrape including sunflower, oilseed rape, and carrot. It has become a recognized agronomic threat in western France (**Gibot-Leclerc *et al.*, 2004**) and has been recorded for the first time in Australia, Central America, and the United States (**Boari *et al.*, 2003**). Branched broomrape is responsible for significant yield losses in tobacco, cabbage, and tomato in Italy (**Boari and Vurro, 2004; Boari *et al.*, 2003; Zonno *et al.*, 2000**). In addition, *Orobanche ramosa* has caused great damage to both field and greenhouse tomato crops in Egypt where *Orobanche* spp. are widespread on winter crops and recently were proposed to be one of the most serious problems in Egyptian agricultural production (**Abdel-Kader and El-Mougy, 2007)**. They parasitize different plants belonging to various families. In heavily infested faba bean fields, the percentage of infection by *Orobanche* could reach up to 90–100% (**Anonymous, 2004a**).

Tomato (*Solanum lycopersicum* L.) is the main field and greenhouse vegetable crop of the coastal areas of the Mediterranean basin (**Tognoni and Serra, 2003; Mauromicale *et al.*, 2005a, 2005b**) and is one of the most important vegetables in Egypt. The total cultivated area in winter, early and late summer plantations reached ∼189 thousand hectars, yielding more than 4 million tons (**Abdel-Kader and El-Mougy, 2007**).

Branched broomrape (*Orobanche ramose* L.) is considered to be one of the most deleterious agents causing losses to tomato production during late summer and winter plantations (**Anonymous, 2004b**). It has been reported that *O. ramosa* reduced the total biomass production of its tomato host by 84% in a surveyed field in Jordan (**Qasem, 1998**). The reduction in biomass was reflected in lowered growth rates, which resulted in a severe reduction in yield. Additionally, *O. ramosa* is a serious threat for the cultivation of tobacco, tomato and hemp in central Europe. Based on field investigations, *O. ramosa* can be found in nearly 50% of tobacco or tomato fields in the Slovak Republic, resulting in severe yield decrease (**Sauerborn, 2003**). Although it is hard to make exact estimates of the above yield losses, due to the difficulty in creating broomrape-free plots for comparison with infested plots, the potential for loss in crop yield due to broomrape infestations is never overestimated.

Moreover, the holoparasite broomrape attacks and severely damages many food and ornamental crops, causing considerable yield losses (**Parker, 1986**).
Neither common control methods for the pathogen nor breeding for resistance have proved successful. As for control measures, some cultural practices and chemical herbicides were tried by many investigators, but they failed to provide satisfactory control against broomrapes infection in many crops such as tobacco, tomato, sunflower and legumes (**Epple and Norris, 1996; Goldwasser *et al.*, 2003; Eizenberg *et al.*, 2004; Economou *et al.*, 2006**).

Weed management in the greenhouses or fields depends on regular preplant soil fumigation with methyl bromide, which also controls branched broomrape. However, the use of this fumigant is compromised by its destructive effect on atmospheric ozone (**Noling and Becker, 1994**). As a result, its use is scheduled to be phased out between 2005 and 2015, according to the revised Montreal Protocol. In the European Union, use of methyl bromide as a soil, commodity, and structural fumigant has been banned since January 1, 2005 (European Regulation CE 2937/2000).

Therefore, there is an urgent need to identify alternative technologies for broomrape control. In southern Italy and other Mediterranean countries, an attractive alternative is soil solarization (**Mauromicale *et al.*, 2001, 2005a, 2005b**), alone or in integration with other methods. This approach has attracted interest in many warm-climate countries because of its effectiveness, simplicity, low cost, and safety for humans, animals, plants, and the environment (**DeVay and Stapleton, 1997**). Solarization entails covering wet soil with transparent polyethylene sheets during the hot season (**Katan *et al.*, 1976**). This serves to trap solar energy, thereby, heating the soil sufficiently to destroy soil pests and microbes. The temperature increase achieved is primarily the result of the elimination of evaporation, but is also partially because of the greenhouse effect created (**Mahrer, 1979**). Its effectiveness has been demonstrated in many countries around the world (**Katan, 1991**). Soil solarization has proven to be among the most effective methods of broomrape control in open field crops (**Haidar and Sidahmad, 2000; Mauromicale *et al.*, 2001; Sauerborn *et al.*, 1989**).

Therefore, the main objective of this work was to evaluate the effectiveness of soil solarization by comparing with chemical (e.g., NPK, H_3PO_4, or Gesaprim) or organic (e.g., mixture of organic manures) treatments through conducting two field experiments in the cultivated summer seasons of 2018 and 2019 for tomato. In addition, to assess the effectiveness of soil solarization in integration with H_3PO_4 or Gesaprim (anti-seed germination of broomrape) using two tomato hybrids (e.g., Lojain 935 and GS-12).

MATERIALS AND METHODS

Survey of branched broomrape in tomato fields:

Survey of branched broomrape (*Orobanche ramosa* L.) infestations in Fayoum Governorate was carried out during three seasons (summer, fall, and winter, 2016) of tomato at flowering stage to assess the incidence and severity of infestation of *O. ramosa* in the cultivated areas. The survey was done by selecting three villages from each of the six provinces (e.g., Fayoum, Itsa, Ibshawai, Tamyia, Sennouris, and Yusuf Al-Seddiq), besides more than 10 fields of at least area of one feddan randomly inspected in every selected village.

The disease assessments include:

1. The percentage of prevalence of the *O. crenata*:

The prevalence or distribution of the *O. crenata* was computed by using the number of fields affected divided by total number of fields assessed and expressed as percentage (Abbes *et al*., 2007) as:

$$\text{Prevalence (\%)} = \frac{\textbf{Number of areas (fields)} \text{ infested by Orobanche}}{\text{Total number of (areas) fields assessed}} \times 100$$

2. The percentage of disease incidence and attack severity (disease severity):

The broomrape infection was expressed as percentage of the above ground visual flowering stalks of *Orobanche* around the host plants in the experimental plot (disease incidence) or their numbers attached to the roots of host plants (attack severity). The incidence of the diseases associated with (*O. ramose*) plants were estimated according to the following formula:

$$\text{Disease incidence \%} = \frac{\text{Number of diseased plants}}{\text{Total number of plants inspected}} \times 100$$

Incidences were estimated using a 0 to 100% scale. On this scale, 0% represents a row in which no *O. ramose* had emerged and 100% represented a row in which all the host plants carried emerged spikes of *O. ramose* **(Mokhtar *et al.*, 2009).**

The attack severity of broomrape infection was calculated by classifying the infected tomato plants into five categories according to the number of attached Orobanche juveniles, i.e. 1, 2, 3, a and more than 4 broomrape juveniles per host plant roots **(Abdel-Kader and El-Mougy (2007)**, and the attack severity for each plot was calculated using the formula described by **Chastanger and Ogawa (1979)** as follows:

$$\text{Attack severity} = \frac{\sum(nxc)}{N} \text{x } 100$$

where: A.S. = Attack severity (Disease severity), n = Number of infected plants per category C = Category number N = Total examinal plants

Site and climate:

Two field experiments were conducted on soils with known history and severe *O. ramose* infestation during the summer seasons of 2018 and 2019, May 15 of each, in a private farm in the village of Garado, Itsa province, Fayoum Governorate, Egypt. The soil of the tested field was naturally infested with branched broomrape (*Orobanche ramosa* L.). Before solarization, the main soil characteristics of the experimental field were 55.5% clay, 29.5% silt, 15.0% sand, pH 7.9, 0.98% total organic matter (OM), 1.8% total nitrogen (N), 170 ppm available phosphorus (P), and 795 ppm exchangeable potassium (K). The local climate is semiarid/Mediterranean with cold to mild winters and hot with almost rainless summers.

Soil solarization:

In the summer seasons of 2018 and 2019, the solarized plot size was 6 × 4 m (24 m^2). During late spring, the soil was ploughed several times to provide a uniform surface and then leveled. One day before mulching, the soil was irrigated to field capacity because solarization is more effective with moist soil (**Katan, 1981**) due to the increased thermal sensitivity of resting structures and improved heat conduction. Solarized plots were covered with 30-µm-thick transparent polyethylene film (≥ 88% total visible transmittance and 20% infrared radiation absorption). The non-solarized soil was similarly tilled and watered. Temperatures were measured 3 times daily in the morning, noon and evening. Temperatures were measured during the solarization period at two different depths (i.e., 5 and 15 cm) for the pots for a period of 30 days.

Experimental design:

The experiments were arranged as a completely randomized block design (CRBD) in split arrangement (2 factors; tomato hybrids and different applications) in 2018, while they were arranged as a CRBD in split-split arrangement (3 factors; tomato hybrids, soil solarization, and different applications) in 2019. Each treatment in the field experiments was replicated 3 times.

Plant materials and planting dates:

Five-week-old tomato transplants (Lojain 935 and GS-12 hybrids) were used for the experiments, and were planted on May 15, August 1, and October 15, 2018 and 2019. Planting was conducted with a within-row planting distance of 40 cm, and an inter-row spacing of 120 cm; this gave a density of 60 plants per plot (24 m^2).

Fertilization program:

Starting from 8 days after transplanting (DAT) and for one month, fertilization was as follows: NPK fertilizer (Super f'eid 19/19/19, Technogreen Company) was added at 2 g L^{-1} for 3 times per week for all plots. Humic acid (Humutech 45%, Technogreen Company) and calcium nitrate (Calcium nitrate 15,5/0/0 + 26 Cao, Evergrow Company) were added to the soil both at a rate of 3 g L^{-1} once weekly. Amino acids (Aminoplus TG 22.5% free amino acids, Technogreen Company) at a rate of 2 cm L^{-1} and a mixture of micro-elements (Fedex, Pharmaceutica Company) at a rate of 2 g L^{-1} were sprayed once a week. Starting from 40 DAT and for another month, the fertilization rates were increased to be as follows: NPK fertilizers were added at 5 g L^{-1} for 3 times weekly. Humic acid and calcium nitrate were added to the soil both at a rate of 5 g L^{-1} once weekly. Amino acids at a rate of 5 cm L^{-1} and a mixture of micro-elements at a rate of 5 g L^{-1} were sprayed once a week. Starting from 70 DAT, K fertilizer levels were increased to an average of 6 times a week. For the field experiments, the fertilization program itself was followed in the field experiments taking into account the area and plant number in each plot. And other Agricultural practices were followed by applying standard commercial practice.

Treatments applied:

These experiments were conducted with Lojain 935 and and GS-12 tomato hybrids because they were the most cultivars of tomatoes infected with *Orobanche ramosa* (L.) compared to other cultivars cultivated in the surveyed tomato areas. Six treatments were applied in the summer season of 2018 for both hybrids as follows:

1. Control (Infected); non-solarized plots, which was naturally infected with *O. ramosa* and not received any treatment applications.
2. Organic manure (OM) treatment; non-solarized plots, which was naturally infected with *O. ramosa* and received 85 kg organic manure (mix of cattle, sheep, and poultry manures at equal amounts) per plot (24 m^2). The OM was well mixed with the surface layer of the plot soil before transplanting.
3. Phosphoric acid (H_3PO_4, 85% conc.) treatment; non-solarized plots, which was naturally infected with *O. ramosa* and received H_3PO_4 in irrigation water at a rate of 2 ml L^{-1} up to the end of experiment.
4. NPK treatment; non-solarized plots, which was naturally infected with *O. ramosa* and received additional dose of NPK at 1, 0.5, and 1 kg per plot (24 m^2). This additional dose of NPK was added once before transplantation by mixing with the plot soil.
5. Gesaprim (a herbicide; anti-seed germination, which contains 80% atrazine as an active ingredient) treatment; non-solarized plots, which was naturally infected with *O. ramosa* and received Gesaprim at a rate of 5 g L^{-1} water. This Gesaprim solution was added before transplantation by irrigation of the soil in each pot with 2 L water versus 2 L water free from Gesaprim for each pot in other treatments. Gesaprim was added once as an anti-seed germination of *O. ramosa*.
6. Solarization treatment; solarzied plots naturally infected with *O. ramosa.*

In the summer season of 2019, three factors; tomato hybrids, soil solarization, and only two treatment application (H_3PO_4 and Gesaprim, which conferred the best results compared to other applications in the last experiments) were applied. The main plots were occupied by tomato hybrids (Lojain 935 and GS-12), the subplots were occupied by solarization or non-solariation, and the sub-subplots were occupied by treatment applications (infected control, H_3PO_4 and Gesaprim). The description of treatment applications as mentioned above.

Incidence and attack severity:

The percentages of incidence and attack severity of *O. ramosa* were calculated from data collected as mentioned above.

Samples of growth parameters and yield components:

Five tomato plants were randomly selected from each treatment of all experiments for all seasons at 50 days after transplantation. Plants were separated into shoots and roots to assess shoot fresh weight per plant. For dry weights, the shoots were placed in an electric oven at 70 °C until constant weights were obtained. At marketable yield stage, the number of fruits per plant and the weight of fruits per plot were assessed using all remaining plants in all treatments.

Statistical analysis:

The experiments were arranged as a completely randomized block design (CRBD) in split arrangement (2 factors; tomato hybrids and different applications) in 2018, while they were arranged as a CRBD in split-split arrangement (3 factors;

tomato hybrids, soil solarization, and different applications) in 2019. The statistical analysis was conducted using Statistica (version 9, Tulsa, OK, USA). All data were compared by using two-way ANOVA, with Tukey's Multiple Comparison Test.

RESULTS

Survey of the distribution of *Orobanche ramosa* in the provinces of Fayoum Governorate in 2016:

Data in **Table 1** show the results of the survey of *Orobanche ramosa* (L.) in the tomato fields during three seasons (e.g., summer, fall and winter) of 2016 at flowering stage in the six provinces of Fayoum Governorate. In summer season 2016, the results indicate that Ibshawai province had the highest percentage of incidence (41.7%) and attack severity (92.3%) (although the lowest area investigated) followed by Itsa province (23.1 and 61.5%, respectively), while Tamyia province showed the lowest percentage of incidence (6.4%) and attack severity (21.4%) followed by Sennouris province (9.1 and 23.6%, respectively).

Table 1. A survey of the distribution of *Orobanche ramosa* (L.) in the six provinces of Fayoum Governorate during three seasons of 2016

Province	***Area of tomato (fed.)**	**No. of tested fields**		**Prevalence (%)**	**Attack severity (%)**
		Infested	Healthy		
	Summer season 2016				
Fayoum	609	13	56	18.8	58.8
Itsa	569	28	93	23.1	61.5
Ibshawai	24	10	14	41.7	92.3
Tamyia	857	14	204	6.4	21.4
Sennouris	587	4	40	9.1	23.6
Yusuf Al-Seddiq	368	7	66	9.6	31.2
	Fall season 2016				
Fayoum	1035	7	280	2.4	2.8
Itsa	1158	9	310	2.8	6.4
Ibshawai	178	2	30	6.3	16.8
Tamyia	764	9	55	14.1	31.4
Sennouris	618	3	50	5.7	18.4
Yusuf Al-Seddiq	115	10	32	23.8	62.6
	Winter season 2016				
Fayoum	1112	52	295	15.0	45.6
Itsa	1932	315	380	45.3	93.9
Ibshawai	344	17	55	23.6	67.4
Tamyia	1085	53	204	20.6	70.4
Sennouris	789	20	48	29.4	88.6
Yusuf Al-Seddiq	989	24	73	24.7	72.8

***Area of tomato in feddans in 2016 seasons, Annual Report of Agricultural Economy and Statistical Department, Ministry of Agriculture, 2016.**

In fall season 2016, Yusuf Al-Seddiq province had the highest percentage of incidence (23.8%) and attack severity (62.6%) followed by Tamyia province (14.1 and 31.4%, respectively), while Fayoum province showed the lowest percentage of incidence (2.4%) and attack severity (2.8%) followed by Itsa province (2.8 and 6.4%, respectively). In winter season 2016, Itsa province had the highest percentage of incidence (45.3%) and attack severity (93.9%) followed by Sennouris province (29.4 and 88.6%, respectively), while Fayoum province showed the lowest percentage of incidence (15.0%) and attack severity (45.6%) followed by Tamyia province (20.6 and 70.4%, respectively). In general, the highest infestations were detected in winter season followed by summer season, while fall season showed the lowest infestations.

Soil temperature:

Data in **Table 2** show the numbers of days when soil temperature was ≥ 40, 45, 50, or 55°C during the solarization period at two soil depths for the field (summer of 2018 and 2019) experiments.

Table 2. Number of days when soil temperature was ≥ 40, 45, 50, or 55°C during the solarization period at two soil depths

Treatment	Depth of 5 cm				Depth of 15 cm			
	≥ 40	≥ 45	≥ 50	≥ 55	≥ 40	≥ 45	≥ 50	≥ 55
Season 2018								
Solarized	88	42	29	15	76	36	21	8
Non-solarized	69	30	19	1	63	29	9	0
Season 2019								
Solarized	90	43	31	14	80	39	23	10
Non-solarized	70	28	18	1	64	31	10	0

Temperatures measured during the solarization period at two different depths in the field in the village of Garado Itsa province for a period of 50 days.

Solarization substantially increased the soil temperature at both depths. Markedly, a temperature above 50°C at 5 cm was recorded for 15 and 14 days (for 2018 and 2019 seasons, respectively) in solarized but for one day (for both 2018 and 2019 seasons) in non-solarized soil. At 15 cm, a temperature above 50°C was recorded for 8 and 10 days (for 2018 and 2019 seasons, respectively) in solarized but for zero (0) day (for both 2018 and 2019 seasons) in non-solarized soil.

The field summer season experiment of 2018:

Effect of chemical, organic or solarization application on *Orobanche ramosa* (L.) incidence and attack severity of tomato hybrids:

The data in **Table 3** show the treatment of chemical, organic or soil solarization applications to control *O. ramosa* infestation. For the tomato hybrids, the incidence and attack severity of *O. ramosa* were higher with the Lojain 935 hybrid by 18.9 and 13.1%, respectively compared to the GS-12 hybrid. Regarding the treatment applications, all application (e.g., organic manure, H_3PO_4, NPK, Gesaprim, and soil solarization) significantly reduced the incidence and attack severity of *O. ramosa* in both tomato hybrids compared to the untreated control. Outperforming Gesaprim, soil solarization was the best treatment with 90.3 and 89.1% reductions of the incidence and attack severity of *O. ramosa*, respectively compared to the infected control. Moreover, the interaction between tomato hybrids and different applications was significant for the reduction in the incidence and attack severity of *O. ramosa*. The interactive treatment of GS-12 × soil solarization was the best application followed by Lojain 935 × soil solarization. These interactive treatments significantly reduced the incidence and attack severity of *O. ramosa* by recording 5.6 and 7.4%, and 8.3 and 11%, respectively versus 62.8 and 71.8%, and 83.4 and 95.3% for the corresponding controls.

Effect of chemical, organic or solarization application on growth parameters of tomato hybrids infected with *Orobanche ramosa* (L.):

The data in **Table 3** display the treatment of chemical, organic or soil solarization applications to control *O. ramosa* infestation in summer season. For the tomato hybrids, the shoot fresh and dry weights of the Lojain 935 hybrid exceeded those of the GS-12 hybrid by 6.1 and 8.1%, respectively. Regarding the treatment applications, all application (e.g., organic manure, H_3PO_4, NPK, Gesaprim, and soil solarization) significantly increased the fresh and dry weights of both tomato hybrids compared to the untreated control. Beyond Gesaprim, soil solarization was the best treatment, increasing the fresh and dry weights by 283.5 and 229.7%, respectively compared to the infected control. Moreover, the interaction between tomato hybrids and different applications was significant for the increase in the fresh and dry weights of tomato hybrids. The interactive treatment of Lojain 935 × soil solarization was the best application followed by GS-12 × soil solarization. These interactive treatments significantly increased the fresh and dry weights by recording 172.3 and 21.7%, and 162.9 and 20.4%, respectively versus 45.3 and 6.8%, and 42.1 and 5.9% for the corresponding controls.

Effect of chemical, organic or solarization application on yield components of tomato hybrids infected with *Orobanche ramosa*:

The data in **Table 3** exhibit the treatment of chemical, organic or soil solarization applications to control *O. ramosa* infestation in summer season. For the tomato hybrids, the fruits No. plant^{-1} and fruits yield plot^{-1} of the Lojain 935 hybrid surpassed those of the GS-12 hybrid by 29.9 and 10.6%, respectively. The fruit yield plot^{-1} of both Lojain 935 and GS-12 hybrids was increased by 170.6 and 147.0%, respectively compared to the infected control. Regarding the treatment applications, all application (e.g., organic manure, H_3PO_4, NPK, Gesaprim, and soil solarization) significantly increased the fruits No. plant^{-1} and fruits yield plot^{-1} of both tomato hybrids compared to the untreated control. Outperforming Gesaprim, soil solarization was the best treatment, increasing the fruits No. plant^{-1} and fruits yield plot^{-1} by 116.4 and 270.0%, respectively compared to the infected control. Moreover, the interaction between tomato hybrids and different applications was significant for the increase in fruits No. plant^{-1} and fruits yield plot^{-1} of tomato hybrids. The interactive treatment of Lojain 935 × soil solarization was the best application followed by GS-12 × soil solarization. These interactive treatments significantly increased the ruits No. plant^{-1} and fruits yield plot^{-1} by recording 29.5 and 221.4%, and 28.4 and 128.6%, respectively versus 14.3 and 56.8%, and 12.4 and 53.9% for the corresponding controls.

Table 3. Response of growth and productivity of tomato hybrids infected with *Orobanche ramosa* to chemical, organic or solarization application (in summer season field experiment, 2018)

Treatments	Infection (%)		Growth parameters		Productivity components		
	Incidence	Attack severity	Shoot FW (g plant^{-1})	Shoot DW (g plant^{-1})	Fruits No. plant^{-1}	Fruits yield (kg plot^{-1})	Yield increase (%)
Hybrids (H)	*	*	*	*	*	*	*
Lojain 935	39.7a	57.0a	126.2a	16.0a	20.0a	153.7a	170.6a
GS-12	33.4b	50.4b	118.9b	14.8b	15.4b	139.0b	147.0b
Appl. (A)	*	*	*	*	*	*	*
Cn (Infected)	67.3a	89.4a	43.7e	6.4e	13.4d	55.4d	-
OM	47.1b	77.3b	123.1c	15.1c	17.1c	135.0c	143.6c
H_3PO_4	25.9c	34.4c	142.2b	17.8b	21.9b	164.3b	196.5b
NPK	47.0b	77.4b	113.9d	14.1d	17.4c	132.8c	139.7c
Gesaprim	25.7c	34.1c	144.6b	18.1b	21.6b	168.1b	203.3b
Solarization	6.5d	9.7d	167.6a	21.1a	29.0a	205.0a	270.0a
H × A	*	*	*	*	*	*	*
L935×Cn	71.8a	95.3a	45.3f	6.8e	14.3e	56.8e	-
L935×OM	50.2c	82.4b	126.4d	15.7cd	16.4d	144.1c	153.7d
L935×H_3PO_4	29.3e	35.8d	146.2b	18.8b	22.0bc	175.8b	209.5bc
L935×NPK	50.3c	81.9b	117.9d	14.1d	16.7d	142.3c	150.5d
L935×Gesap	29.0e	35.3d	148.8b	19.1b	21.1bc	181.9b	220.2b
L935×Solar	7.4g	11.0e	172.3a	21.7a	29.5b	221.4a	289.8a
GS12×Cn	62.8b	83.4b	42.1f	5.9e	12.4e	53.9e	-
GS12×OM	43.9d	72.1c	119.8d	14.4d	17.8d	125.8d	133.4d
GS12×H_3PO_4	22.4f	33.0d	138.2c	16.8c	21.7bc	152.8c	183.5c
GS12×NPK	43.6d	72.9c	109.8e	14.0d	18.1d	123.3d	128.8d
GS12×Gesap	22.3f	32.8d	140.3b	17.0bc	22.1bc	154.3c	186.3c
GS12×Solar	5.6g	8.3e	162.9a	20.4ab	28.4a	188.6b	249.9b

Mean values within columns followed by the same letter are not significantly different ($P \leq 0.05$). Cn = control, OM = organic manure, H_3PO_4 = phosphoric acid, NPK = nitrogen, phosphorus and potassium fertilizers, Solar = solarized, L935 = Lojain 935, FW = fresh weight, and DW = dry weight.

The field summer season experiment of 2019:

Effect of integrative treatment of solarization with phosphoric acid or Gesaprim on *Orobanche ramosa* incidence and attack severity of tomato hybrids:

The data in **Table 4** show the integrative treatment of soil solarization with phosphoric acid (H_3PO_4) or Gesaprim applications to control *O. ramosa* infestation in summer season of 2019. For the tomato hybrids, the incidence and attack severity of *O. ramosa* of the Lojain 935 and GS-12 hybrids were not significant. They recorded 25.2 and 27.7%, and 26.2 and 29.0% to both hybrids, respectively. Regarding soil solarization treatment, soil solarization significantly reduced the incidence and attack severity of *O. ramosa* by 86.8 and 84.8% compared to non-solarization. Regarding the treatment applications, Gesaprim exceeded H_3PO_4 treatment and reduced the incidence and attack severity of *O. ramosa* by 68.7 and

68.9% compared to the infected control. Furthermore, the interaction among tomato hybrids, soil solarization and different treatment applications was significant for the reduction in the incidence and attack severity of *O. ramosa*. The interactive treatment of Lojain 935 × soil solarization × Gesaprim was the best application followed by GS-12 × soil solarization × Gesaprim. These interactive treatments significantly reduced the incidence and attack severity of *O. ramosa* by recording 3.3 and 4.0%, and 3.6 and 4.3%, respectively versus 80.8 and 86.6%, and 82.2 and 88.4% for the corresponding controls.

Table 4. Response of growth and productivity of tomato hybrids infected with *Orobanche ramosa* to integrative treatment of solarization with phosphoric acid or Gesaprim (in summer season field experiment, 2019)

Treatments	Infection (%)		Growth parameters		Productivity components		
	Incidence	Attack severity	Shoot FW (g plant^{-1})	Shoot DW (g plant^{-1})	Fruits No. plant^{-1}	Fruits yield (kg plot^{-1})	Yield increase (%)
Hybrids (H)	ns	ns	*	*	*	*	*
Lojain 935	25.2	27.7	156.4a	19.0a	22.6a	165.6a	165.3a
GS-12	26.2	29.0	135.3b	16.2b	21.1b	148.0b	152.8b
Solarization (S)	**	**	**	**	*	**	*
Non-solarization	45.4a	49.2a	110.8b	13.7b	18.7b	121.9b	101.7b
Solarization	6.0b	7.5b	180.8a	21.5a	25.0a	191.7a	216.4a
Applications (A)	**	**	**	**	*	**	*
Cn (Infected)	45.3a	49.9a	104.0c	13.0c	18.9c	116.6c	92.6c
H_3PO_4	17.7b	19.7b	160.3b	18.9b	22.1b	169.1b	179.4b
Gesaprim	14.2c	15.5c	173.2a	20.9a	24.6a	184.7a	205.3a
H × S × A	*	*	*	*	*	*	*
L935×NonS×Cn	80.8a	86.6a	55.4h	7.3g	15.8gh	62.4f	-
L935×NonS×H_3PO_4	29.2b	32.4b	146.1ef	17.5de	20.4ef	152.6de	144.6f
L935×NonS×Gesap	24.3b	25.8b	158.2de	19.2cd	22.2cde	164.8cd	164.1def
L935×Solar×Cn	8.8c	11.9c	167.5d	20.6c	23.6bcd	182.6bc	192.6cd
L935×Solar×H_3PO_4	5.0c	5.3cd	198.4ab	23.4b	25.2bc	202.4b	224.4b
L935×Solar×Gesap	3.3c	4.0d	212.6a	26.1a	28.4a	228.6a	266.3a
GS12×NonS×Cn	82.2a	88.4a	50.2h	6.8g	13.6h	58.6f	-
GS12×NonS×H_3PO_4	30.7b	34.1b	122.4g	14.9f	18.8fg	140.2e	139.2f
GS12×NonS×Gesap	25.4b	28.0b	132.6fg	16.6ef	21.6def	152.8de	162.5ef
GS12×Solar×Cn	9.2c	12.6c	142.8ef	17.4def	22.4cde	162.7cd	177.6de
GS12×Solar×H_3PO_4	6.0c	6.8cd	174.2cd	19.8cd	24.0bcd	181.2c	209.2bc
GS12×Solar×Gesap	3.6c	4.3d	189.5bc	21.7bc	26.2ab	192.4b	228.3b

Mean values within columns followed by the same letter are not significantly different ($P \leq 0.05$). ns= not significant. Cn = control, H_3PO_4 = phosphoric acid, Gesap = Gesaprim, NonS = non-solarized, Solar = solarized, FW = fresh weight, DW = dry weight, and L935 = Lojain 935.

Effect of integrative treatment of solarization with phosphoric acid or Gesaprim on growth parameters tomato hybrids infected with *Orobanche ramosa*:

The data in **Table 4** show the integrative treatment of soil solarization with phosphoric acid (H_3PO_4) or Gesaprim applications to control *O. ramosa* infestation in summer season of 2019. For the tomato hybrids, the shoot fresh and dry weights of the Lojain 935 hybrid exceeded those of the GS-12 hybrid by 15.6 and 17.3%, respectively. Regarding soil solarization treatment, soil solarization significantly increased the shoot fresh and dry weights by 63.2 and 56.9% compared to non-solarization. Regarding the treatment applications, Gesaprim surpassed H_3PO_4 treatment and increased the shoot fresh and dry weights by 66.5 and 60.8% compared to the infected control. Furthermore, the interaction among tomato hybrids, soil solarization and different treatment applications was significant for the increase in the shoot fresh and dry weights of tomato hybrids. The interactive treatment of Lojain 935 × soil solarization × Gesaprim was the best application followed by GS-12 × soil solarization × Gesaprim. These interactive treatments significantly increased the shoot fresh and dry weights by recording 212.6 and 26.1%, and 189.5 and 21.7%, respectively versus 55.4 and 7.3%, and 50.2 and 6.8% for the corresponding controls.

Effect of integrative treatment of solarization with phosphoric acid or Gesaprim on yield components of tomato hybrids infected with *Orobanche ramosa*:

The data in **Table 4** show the integrative treatment of soil solarization with phosphoric acid (H_3PO_4) or Gesaprim applications to control *O. ramosa* infestation in summer season of 2019. For the tomato hybrids, the fruits No. plant^{-1} and fruits yield plot^{-1} of the Lojain 935 hybrid exceeded those of the GS-12 hybrid by 7.1 and 11.9%, respectively. Regarding soil solarization treatment, soil solarization significantly increased the fruits No. plant^{-1} and fruits yield plot^{-1} by 33.7 and 57.3% compared to non-solarization. Regarding the treatment applications, Gesaprim exceeded H_3PO_4 treatment and increased the fruits No. plant^{-1} and fruits yield plot^{-1} by 30.2 and 58.4% compared to the infected control. Furthermore, the interaction among tomato hybrids, soil solarization and different treatment applications was significant for the increase in the fruits No. plant^{-1} and fruits yield plot^{-1} of tomato hybrids. The interactive treatment of Lojain 935 × soil solarization × Gesaprim was the best application followed by GS-12 × soil solarization × Gesaprim, which increased the fruits No. plant^{-1} and fruits yield plot^{-1} by recording 28.4 and 228.6%, and 26.2 and 192.4%, respectively versus 15.8 and 62.4%, and 13.6 and 58.6% for the corresponding controls.

DISCUSSION

The survey of the distribution of *Orobanche ramosa* in the six provinces of Fayoum Governorate during three seasons of 2016 (**Table 1**) indicated that Ibshawai, Yusuf Al-Seddiq, and Itsa were the most provinces infested with *O. ramosa* in the summer (by 41.7%), fall (23.8%) and winter (45.3%) seasons, respectively. This result may be attributed to the moderate water irrigation, which moderately flood the soil with water for this crop in these provinces, which encourages the seeds of *O. ramosa* present in the soil and increases the number of attachments of *O. ramosa* to tomatoes as the host plant. In contrast, Tamyia, Fayoum and Fayoum were the lowest provinces infested with *O. ramosa* in the summer (by 6.4%), fall (2.4%) and winter (15.0%) seasons, respectively. This result may be attributed to the high water of irrigation, which floods the soil with enough water for this crop in these provinces, which negatively affects the seeds of *O. ramosa* present in the soil and reduces the number of attachments of *O. ramosa* to tomatoes as the host plant. These results are consistent with **Zahran (1977)**, who reported that long periods of flooding the soil reduced the number of attachments of broomrapes to the host plants.

Treatments of organic manures (OM), NPK fertilizers, H_3PO_4, and Gesaprim conferred tomato plants to well compete with branched broomrape (*O. ramosa*) compared to untreated plants (**Tables 3** and **4**). Due to its wealth in essential mineral nutrients and humic substances, OM has the ability to boost tomato plants (**Rady, 2011**) for competetiveness against *O. ramosa*. On the other hand, H_3PO_4, and Gesaprim contributed to kill the seeds of *O. ramosa* to minimize attachments of *O. ramosa* to tomato plants (**Abd El-Wahab *et al.*, 2017**). Due to its wealth in essential mineral nutrients and humic substances, OM has the ability to boost tomato plants in order to compete against *O. ramosa*.

Under the Mediterranean conditions of Egypt, soil solarization has proven to be an excellent method for a fairly complete control of branched broomrape (*O. ramosa*) infestation (**Abouziena and Haggag, 2016**) (**Tables 3** and **4**). In addition, solarization was able to consistently improve tomato yield under greenhouse conditions, where branched broomrape is particularly destructive (**Qasem, 1998; Qasem and Kasrawi, 1995**). Without solarization treatment, branched broomrape consistently decreased plant growth and fruit yield. As the severity of the infestation increased (especially in winter season), the growth of tomato plants was increasingly inhibited (**Tables 3** and **4**). The incidence of chlorosis on plants was increased and the photosynthetic rate was reduced (**Mauromicale *et al.*, 2005a**), and plants tended to have a yield collapse. Results of this study showed that tomato plant growth and fruit yield and its components were negatively and significantly correlated with the incidence of infestation, attack severity, and number of branched broomrape shoots per tomato plant.

Soil solarization as a sole treatment provided a fairly complete control of *O. ramosa* because shoot emergence from treated soil was fairly inhibited (**Tables 3** and **4**). On the other hand, soil solarization as an integrative treatment with Gesaprim (an anti-seed germination of *O. ramosa*) or phosphoric acid (H_3PO_4) provided a complete control of *O. ramosa* because shoot emergence from treated soil was completely inhibited. In addition, no haustoria or underground tubercles were found on the tomato roots at the end of the crop cycle (**Mauromicale *et al.*, 2005a**). The high soil temperatures achieved by solarization/mulching as a single treatment inhibited seed germination of branched broomrape (*O. ramosa*) and killed more than 75% of the buried seed, preventing them to germinate and may be caused secondary dormancy in some of the remaining seeds in the soil of field experiments (summer season of 2018; **Table 3**). In addition, soil solarization as a sole treatment inhibited seed germination of *O. ramosa* and killed more than 90% of the buried seeds, preventing them to germinate and may be caused secondary dormancy in some of the remaining seeds in the soil of field experiments (summer season of 2018; **Table 3**). On the other hand, soil solarization as an integrative treatment with Gesaprim or H_3PO_4 (especially, Gesaprim) inhibited seed germination of *O. ramosa* and killed more than 95% of the buried seeds, preventing them to germinate and may be caused secondary dormancy in the remaining seeds in the soil of field experiments (summer season of 2019; **Table 4**). These results are important because they indicate that the soil seedbank of branched broomrape (*O. ramosa*) seed should be reduced after each solarization. These results are also consistent with those of **Mauromicale *et al.* (2005a)** and **Das *et al.* (2020)**, who predicted that a number of consecutive soil solarizations will lead to limiting the number of parasite seeds in the soil to a level where the normal development of the tomato crop is not influenced. **Mauromicale *et al.* (2000)** and **Mauromicale *et al.* (2005a)** demonstrated that field experiments are planned to evaluate the degree of the viability of branched broomrape seeds buried naturally in the soil after a number of achievements of soil solarization because the exposure of broomrape seeds to high temperatures led to a considerable progressive decrease in germination and a linear reduction in the viability of the seeds.

Soil solarization treatment, especially in integration with Gesaprim improved the growth of tomato plant and, consequently, the fruit yield (**Table 4**). Fruit yield was estimated at 191.7 kg per plot (24 m^2) with soil solarization versus 121.9 kg per plot with non-solarization, an increase of 57.3% in favor of soil solariation. This considerable increase in tomato fruit yield by soil solarization in integration with Gesaprim addition to the soil as anti-broomrape seed germination is largely attributable to the absence of branched broomrape infestation. However, there are additional beneficial effects conferred by the treatment of soil solarization (e.g., the control of soil-borne diseases, the increased release and uptake of macro- and micronutrients, the release of plant growth regulators, the improvement of mycorrhizal growth, and the increase in endogenous gibberellins supply) that cannot be ruled out (**Chen *et al.*, 1991; Grunzweig *et al.*, 2000; Mauromicale *et al.*, 2005a, 2005b**). These reports also indicated that, given the high correlation between yield and the infestation with branched broomrape, as well as the absence of soil-borne pathogens, and the optimal plant nutrition maintained over the crop cycle, the additional beneficial effects conferred by soil solarization are maybe slight compared with the adverse impacts of the branched broomrape populations.

Applying Gesaprim herbicides to the soil at a safe level does not cause health risks to humans and animals (**Abd El-Wahab *et al.*, 2017**). Fate of herbicide in soil depends on number of processes such as volatilization, leaching, runoff and degradation by microbes, chemical processes and photodecomposition. Meanwhile, **Appleby (1985)** reported that organic matter can be a major reason for a wide variation in plant response to seven herbicides concentration in the soil. Additionally, **Mayer (1987)** stated that some herbicides may be available to plants as a vapor in the phase of the soil, but most must be present in the soil solution before they can be absorbed by the germinating weed seedling. **Nasseri (2009)** reported that atrazine (an active ingredient of Gesaprim) leaching and dissipation rate in different soil profiles in the four sampling regions were high and significant. Therefore, there is a high risk of atrazine pollution in groundwater resources of the region. However, in the present study, Gesaprim was applied at a level of 5 g per L of water (the recommended dose according to the constructions of Ministry of Agriculture, 2014, Egypt.). This concentration of Gesaprim is safe and does not contaminate the environment (**Abd El-Wahab *et al.*, 2017**). Therefore, the application of Gesaprim to the soil at the above-mentioned safe level is more effective in integration with soil solarization to completely kill the seeds of branched broomrape (*O. ramosa*), which positively reflected on the growth and yield of tomato plants (**Table 4**).

In the present study, the control of branched broomrape (*O. ramosa*) in fields or greenhouses by soil solarization in integration with soil applied with Gesaprim as anti-broomrape seed germination was more effective than soil solariation alone in minimizing incidence and attack severity of *O. ramosa* and maximizing the growth and fruit yield of tomato plants (**Table 4**). As we know, branched broomrape attack is currently a significant risk. Where cultivation of some crops has been abandoned due to the high infection with *Orobanche* and low levels and stability of crop yields (**Foti, 1994**), the adoption of soil solarization, especially in integration with soil application with Gesaprim may be able to rescue the production of these crops (**Mauromicale *et al.*, 2005a**). There are many advantages to using soil solarization: specifically, it is a simple, non-chemical, non-hazardous method, which avoids the use of any toxic substances, does not pollute the site, and therefore it is suitable for organic farming or other low-input agricultural systems.
Using soil solarization (and other solar energy) in agriculture will become more important (**Stapleton, 2000**) due to that it is a non-chemical method successfully used in many countries to control or reduce soil borne plant pathogens, weeds and mites. Soil solarization includes the use of transparent polyethylene sheeting to trap the heat from solar radiation to raise soil temperature to levels that are lethal to weed seeds and seedlings. In this regard, **Haidar and Sidahmed (2000)** reported that solarization for 2, 4, or 6 weeks with chicken manure has increased the average weight of cabbage plants by 55, 70, or 75%, respectively compared to the control with chicken manure. **Candido *et al.* (2011)** reported that the average lettuce marketable yield was always found significantly higher in solarized soil than in untreated control in both greenhouse and in the field. **Schreiner *et al.* (2001)** stated that soil solarization is a promising method to reduce the populations of soil-borne pests and weeds without using pesticides. Weed control effectiveness is dependent on moist soil, sufficiently high air temperatures and solar radiation, and an adequate length of exposure. Moist soil is essential to heat conductivity and for keeping seeds in a more susceptible imbibed state. The effects of solarization on weed emergence were apparent for a short time after plastic was removed. During the first two months after removal, the number of emerging annuals was less than 15% of an untreated check (**Abouziena and Haggag, 2016**). The possible mechanisms of weed, including *Orobanche* spp. control by soil solarization are as follows: 1) thermal killing of seeds, 2) thermal killing of seeds induced to germinate, 3)

breaking seed dormancy and consequently killing the germinating seeds, and 4) biological control through weakening or other mechanisms. Only clear (transparent) plastic reduced weed population for one year after soil solarization (**Zimdahl, 2013**). During solarization, In Egypt, the soil temperature reached 69^{o}C, under solarization mulching (**Fayed *et al.*, 1997**). The effect of solarization is greater at top 5- to 10-cm layer than at lower layers. This explains the efficacy of solarization on weed seed germination and seedling growth.

For the tomato cultivars, although Lojain 935 was more infected with *O. ramosa* than GS-12, it was more tolerant to *O. ramosa* and generated more growth parameters and fruit yield component, especially when applied with soil solarization in integration with Gesaprim (**Table 9**). This result may be due to the fact that Lojain 935 has a larger canopy and rapid growth, allowing this hybrid to tolerate this *O. ramosa*.

Finally, it could be concluded that successful and sustainable branched broomrape (*Orobanche ramosa*) management systems are those that use an integration among techniques rather than depend on one method. As global environmental quality considerations become more important, along with a growing population, advanced concepts, such as soil solarization and other uses of solar energy in agriculture, will become more important. Further research is necessary for new technologies and methods for weed control in clean agriculture to determine the degree of branched broomrape seedbank viability down the soil profile and its relationship with soil temperature reached during soil solarization to facilitate strategies to completely eradicate the parasite weed from the soil. However, To reach full control of *O. ramosa*, soil solarization should be integrated with other application such as Gesaprim at a safe concentration (5 g L^{-1} of water).

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الملخص العربي

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تعتبر زراعة الطماطم في منطقة حوض البحر الأبيض المتوسط عرضة للإصابة بالأعشاب الطفيلية المتفرعة مثل الهالوك (*Orobanche ramosa*) ويمكن أن تؤدي إلى خسائر كبيرة في المحصول. تم دراسة كفاءة تشميس التربة كمعاملة فردية (تقنية تطهير التربة التي تستخدم التسخين الشمسي السلبي) أو بالتكامل مع مبيد الحشائش جيسابريم (أو حامض الفوسفوريك) لمكافحة الإصابة بالـ *Orobanche ramosa* وبالتالي زيادة نمو وإنتاج الطماطم (هجيني لوجين ٩٣٥ و جي إس-١٢) في ظل ظروف تجارب الحقل خلال موسمي صيف ٢٠١٨ و ٢٠١٩. أوضح الحصر/المسح لتوزيع الـ *Orobanche ramose* والذي تم تنفيذه في مراكز محافظة الفيوم الستة لعام 2016 أن أعلى نسبة وشدة إصابة كانت في مراكز يوسف الصديق، أبشواي وإطسا، في حين أن أدنى نسبة وشدة إصابة كانت في مراكز طامية والفيوم. وكانت أعلى نسبة وشدة إصابة في موسم الشتاء، بينما أظهر موسم الخريف أدنى نسبة وشدة إصابة. في تجارب الأصص والحقل، كانت معاملة تشميس التربة أفضل المعاملات الفردية مقارنةً بمعاملات السماد العضوي، حامض الفوسفوريك، سماد NPK، و الجيسابريم لمكافحة هالوك *O. ramosa* وزيادة قياسات النمو والمحصول لهجن الطماطم. بالإضافة إلى أن معاملة تشميس التربة بالتكامل مع الجيسابريم (أو حامض الفوسفوريك) كانت أفضل معاملة تكاملية للهجين لوجين ٩٣٥ متبوعة بنفس المعاملة التكاملية للهجين جي إس-١٢. هذه المعاملة التكاملية الأفضل خفضت نسبة و شدة الإصابة بالـ *O. ramosa* إلى أدنى مستوى ممكن وزودت قياسات النمو (الأوزان الطازجة والجافة للمجموع الخضري لكل نبات) ومكونات المحصول (عدد ثمار الطماطم لكل نبات و محصول الثمار لكل نبات أو لكل قطعة تجريبية) إلى أعلى مستوى ممكن مع تفوق الهجين لوجين ٩٣٥ في هذا الصدد. بناء على ذلك، فإن هذه الدراسة توصي باستخدام التطبيق التكاملي الأفضل (تشميس التربة × الجيسابريم - أو حامض الفوسفوريك) كتقنية مناسبة لإنتاج الطماطم حيث وجود أخطار الإصابة العالية بالهالوك المتفرع.

الكلمات المفتاحية: إنتاج الطماطم، تشميس التربة، الهالوك، الأعشاب الطفيلية، الجيسابريم، حامض الفوسفوريك، السماد العضوي، سماد NPK.