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Soil solarization and biosolarization for controlling crown and root rot disease complex of greenhouse tomato under hysteretic soil conditions

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Abstract

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This study revealed the effectiveness of pre-plant soil solarization and biosolarization against the crown and root rot disease complex of greenhouse tomatoes in soils "locked in" by hysteretic performance as a result of multiple applications of broad-spectrum disinfestation methods, which are non-selective to indigenous soil microbial communities. Greenhouse pot experiments were conducted using naturally infested soil containing the principal pathogen, *Fusarium oxysporum* f.sp. *radicis-lycopersici* and associated species, including *Colletotrichum coccodes, Fusarium solani, Pyrenochaeta lycopersici, Rhizoctonia solani* AG 4 and AG 6, *Sclerotinia sclerotiorum, Pythium* spp., and *Phytophthora* spp. Soil was collected from a tomato production glasshouse with a long history of disease, where annual chemical soil fumigation or heat steaming had ceased to have a positive effect on plant health or yields. Soil was filled into transparent polyethylene bags, either with or without incorporation, at different rates of fresh tomato residues cut into pieces 2–4 cm in length. The bags were left open (untreated controls) or tightly closed and exposed to the sun for 7 to 30 days. Treated and untreated soils were transferred to plastic pots, along with tomato plants. Ideals were cultivated for 75 days. Thirty-day solarization reduced the severity of crown and root rot by 40.9%. Biosolarization with the addition of tomato-crop residues at a maximum rate of 100 g L^{-1} soil, followed by 30-day solarization, provided the highest level of disease control – 52.5%. The incorporation of fresh tomato crop residues without subsequent solar heating had no disease-modifying effect or led to an increase in disease symptoms. No follow-up disease-suppressive effect was observed during a second cropping cycle in the same soils. However, both ecologically benign methods have demonstrated that they can break the tendency of the boomerang effect and overcome the condition of hysteresis in soil ecosystems subjected to pulse disturbances by drastic, pathogen-eradicating treatments.

Keywords: complex etiology; associated pathogens; soil disinfestation; buffering capacity; resilience; hysteresis

Introduction

Crown and root disease complex is the most economically crucial biological constraint to the production of greenhouse tomatoes in Bulgaria and elsewhere in the World. The disease is particularly destructive in soil-based systems, including both glass- and plastic greenhouses, with a relatively long history of intensive vegetable growing and tomato cultivation in monoculture. A shifting range of major soilborne fungal and fungal-like pathogens have been found associated with the crown and root rot of tomato, including *Fusarium oxysporum* Schlechtend.: Fr. f. sp. *radicis-lycopersici* Jarvis and Shoemaker (FORL), *Colletotrichum coccodes* (Wallr.) Hughes, *Fusarium solani* (Mart.) Sacc., *Pyrenochaeta lycopersici* Schneider and Gerlach, *Rhizoctonia solani* Kühn AG-4 and AG-6, *Sclerotinia sclerotiorum* (Lib..) de Bary, *Pythium aphanidermatum* (Edson) Fitzp., *P. ultimum* Trow, *Phytophthora nicotianae* var. *nicotianae*

Breda de Haan, *P. capsici* Leonian, other *Fusarium* spp. and *Oomycetes* (Vatchev, 1995; 2013; 2016). The disease syndrome is primarily characterized by symptoms and signs of Fusarium crown and root rot (FCRR), caused by FORL, the most prevalent soilborne pathogen affecting tomatoes in the country. Although FORL has been reported as the dominant causal agent associated with the crown and root rot disease complex, each of the other aforementioned fungal and fungal-like pathogens appears to have a significant role in the complex etiology of the disease (Vatchev, 1995, 2013).

In most cases, the inocula of all the pathogens coexist in the soil before planting. Therefore, pre-plant soil disinfestation has been recognized as a key preventive strategy for managing the disease in tomato production. Although chemical fumigation and steaming have been found to effectively reduce soilborne pathogens (Chellemi et a., 1994; Ozbay and Newman, 2004), since the first reported attempts to control Fusarium crown and root rot of tomatoes, evidence has accumulated that the disease becomes more severe in either steam "sterilized" or chemically fumigated soils (Farley et al., 1975; Jarvis et al., 1975; Jarvis, 1988). Convincing arguments were provided that as a result of such eradicative treatments, populations of soil microbial competitors and antagonists were drastically reduced, which led to rapid reinvasion of the treated soil by the airborne-dispersed causal pathogen, and was followed by complete disease control failure (Jarvis et al., 1977; Rowe et al., 1977; Rowe and Farley, 1978; Marois and Mitchell, 1981; McGovern and McSorley, 1997). Notwithstanding these findings, for the next three decades, eradication approaches such as pre-planting soil fumigation or heat treatment through soil steaming were routinely recommended and widely applied in attempts to control certain soilborne diseases and pests in tomato production (McGovern et al., 1998; Gilreath et al., 2005).

Notably, earlier studies (Kreutzer, 1960; Altman et al., 1970; Baker and Cook, 1974; Bollen, 1974) as well as more recent works (Chen et al., 1991; Katan and DeVay, 1991; Wing et al., 1995) reported an increase in severity of various soilborne diseases in response to broad-spectrum chemical fumigation or steam heating of pathogen-infested soils. The phenomenon has become known as "disease accentuation" or the "boomerang effect" and has been well established in plant pathology, as well as in nematology literature. It has been attributed to drastic perturbation and dramatic decrease in populations of non-target indigenous and antagonistic soil microbiota, which in turn creates a partial or near "biological vacuum" in treated soils As a result, a reinvasion and rapid build-up of plant pathogenic populations have been observed (Cook and Baker, 1983; Van Bruggen et al., 2006; Domínguez-Mendoza et al., 2014).

Our previous research and observations comprising more than 70 greenhouse tomato production units (glass-, net- or plastic-covered structures) in the country and beyond established that recurrent eradicative treatments – three to four in succession, performed over eight to ten years to the same greenhouse soil, irreversibly and permanently eliminated biological buffering capacity or resilience (Szabolcs, 1994) of soil microbial communities against reinvasion of the soil (Baker, 1957) by pathogens associated with crown and root rot disease complex of tomato (Vatchev, 2004; 2016). Moreover, while after the first, the second and the third consecutive treatment, the soil still had the natural biological capacity to counteract the invasion and recolonization by pathogens, and to delay the onset of the disease by three, two and one year, respectively, any subsequent treatments failed to suppress or retard the disease outbreaks and to prevent crop losses during the cropping season to follow (see discussion section below, Vatchev, 2016). Under these circumstances, the level of disease suppression remained critically low. It did not recover within several consecutive years, even after discontinuing the repetitive applications of biocidal means of soil treatment. Arguments were advanced that, in response to the repetitive applications of non-selective soil disinfestation methods, a critical condition known as hysteresis (Lal, 1997; Wilson and Tisdell, 2001) occurred in the soil ecosystem. The hysteresis condition manifested as a highly disease-conducive environment, in which resident microbial communities involved in natural disease suppression were unable to recover even after the termination of pathogen-eradicative treatments. Generally, hysteresis reflects the inability of a system to recover to its original state after perturbations entirely or refers to the slow recovery of the system's functioning once the source of the disturbance is no longer present (Lal, 1997; Seybold et al., 1999; Valone et al., 2002; Potts et al., 2006; Baer et al., 2012). In a broad sense, hysteresis has also been referred to as a "memory phenomenon" (Von Bertalanffy, 1968) and a "path-dependent process," meaning that history and previous conditions influence the system's present state and its future development (Lal, 1997; Jørgensen, 2002; Grandy et al., 2012).

In our previous research, as well as in the current study, the condition of hysteresis has been characterized by a complete lack of control over crown and root rot of tomatoes, despite any prior treatments aimed at ensuring the total eradication of plant pathogens from the soil (Vatchev, 2016). By previous studies on sustainable management of ecosystems showing hysteresis (Seybold et al., 1999; Scheffer et al., 2001; Wilson and Tisdell, 2001; Grandy et al., 2012; Song et al., 2015), we postulated that a shift from total eradication approaches to more selective and biologically-based disinfestation strategies would help the hysteretic soil ecosystem to recover its biological buffering capacity. This should keep the disease under control.

The efficiency of soil solarization, a process based on capturing and passively accumulating solar energy in treated soil, may be significantly affected by various ambient and weather conditions (Stapleton, 2000, 2016). To enhance the effectiveness of solar treatment and ensure the longevity of the results, an alternative approach combining solarization with the application of various organic soil amendments has been recently developed. This approach has been successfully applied in many crop production systems (Stapleton, 2000; Ros et al., 2008; Gamliel and van Bruggen, 2016), and has been recently referred to as "biosolarization" (Stapleton et al., 2016; Birthisel et al., 2019). The authors used different yet semantically related terms to depict a disinfestation technique which implies the incorporation to soil of raw organic materials or byproducts (Blok et al., 2000; Stapleton, 2000; Strauss and Kluepfel, 2015) as a C source followed by irrigation, covering the treated soil with transparent plastic film, without (Núñez-Zofío et al., 2010; Strauss and Kluepfel, 2015) or with additional exposure to sun for a defined period (Butler et al., 2014), e.g. 3–6 weeks (Gamliel and van Bruggen, 2016).

To overcome constraints of tomato production, soil solarization and biosolarization have been widely used as more ecologically benign alternatives, pursuing reduction of soilborne pathogens (Lombardo et al., 2012; Momma et al., 2013; Gamliel and van Bruggen, 2016; Paudel et al., 2018; Testen et al., 2021), plant-parasitic nematodes (Elmore et al., 1997; Kaşkavalci, 2007; Oka et al., 2007), insect pests and weeds (Katan, 1981; DeVay and Katan, 1991; Lombardo et al., 2012). Additionally, both methods exert a less harmful impact on the indigenous soil microbiota (Wang et al., 2021).

To date, there are no published articles on the potential of these ecologically more benign soil disinfestation methods to control plant pathogens in soils, where multiple applications of drastic sterilization methods have given rise to a boomerang effect, subsequently leading the soil ecosystem to hysteresis. Neither are there any reports on the performance of soil solarization or biofumigation for controlling the crown and root rot disease complex of tomato under those ecological circumstances. Furthermore, it has been demonstrated that the suppressive effect of solarization is not limited to the initial growing season following treatment and, in some cases, may last more than a year (Katan et al., 1983; Klein et al., 2012; Özaslan et al., 2015). Little experimental work has been done to substantiate these findings.

The objective of this study was to evaluate the effectiveness of soil solarization (applied alone) and biosolarization with raw tomato crop residues as a soil amendment for controlling the crown and root rot disease complex of tomato. The evaluations were carried out under soil conditions of hysteresis, characterized by a decline in disease control after multiple applications of eradicative biocidal treatments to the soil. Another objective of the study was to assess the duration of disease control achieved by the evaluated soil disinfestation treatments under the aforementioned conditions.

Materials and Methods

About the objectives of the study, three individual experiments were carried out: first, to evaluate the effectiveness of different periods of soil solarization (experiment 1); second, to compare the effects of solarization and biosolarization (experiment 2) and the third, to determine the duration of the protection provided by the two disinfestation practices by planting a second tomato crop in the same soils (experiment 3).

Soil origin and condition

The soil used in the present study was collected from a commercial greenhouse of Rosella Ltd in Simitli (41°53′18.70″N and 23°06′31.71″E), Blagoevgrad District, with a cropping history of more than 35 years, including tomatoes as a primary winter crop and cucumbers as a short summer crop. The texture of the soil was coarse sandy clay loam, with 53.0% sand, 38.3% clay, 9.7% silt, 0.3% organic matter, and a pH of 7.04. The greenhouse had a long history of severe crown and root rot of tomato. Our preliminary observations revealed that the soil was "naturally" infested, although not on the same frequency, with *F. oxysporum radicis-lycopersici* (FORL), *Colletotrichum coccodes*, *Pyrenochaeta lycopersici*, *Rhizoctonia solani* AG 4 and AG 6, *Sclerotinia sclerotiorum*, *Pythium aphanidermatum*, *P. ultimum*, *Phytophthora nicotianae var. nicotianae* (Vatchev, 2016). The greenhouse soil had been frequently steam-sterilized at nearly 100°C in the past or chemically fumigated using various formulations of methyl bromide-chloropicrin mixtures, mixtures of 1,3-dichloropropene and 1,2-dichloropropane (DD), and metam sodium. According to records provided by greenhouse growers (Z. Uzunova, *personal communication*), these preplant biocidal treatments initially gave a relatively good level of control over root diseases in greenhouse tomatoes. Later, typical of hysteresis phenomena, a decline in disease control associated with eradicative soil disinfestation was consistently observed. For 12 consecutive years prior to the onset of this study, the greenhouse soil was annually fumigated with broad-spectrum methyl bromide-chloropicrin mixtures, considered the most effective soil fumigant, but with no positive impact on plant health or yields. A double-crop system had been implemented for years, utilizing tomatoes as a primary winter crop and cucumbers as a short summer crop.

Soil sampling and maintenance

For experiments 1 and 2 in this study, at least 20 soil subsamples were collected from 10 separate greenhouse bays at depths of 5 to 20 cm. Subsamples were thoroughly mixed with a spade (to produce a composite sample), sieved through 20 mm mesh sieves, filled in clean plastic containers, and transported to the experimental greenhouse for immediate experimentation. In one case (the repetition of Experiment 1), the soil was stored for a short period of four days in the shade at 14–16°C prior to the application of soil treatments. For the third experiment, solarized, biosolarized, and untreated soils were obtained from the respective treatments of Experiment 2 and used for further biological testing without any additional treatment.

Soil disinfestation treatments

To test the effectiveness of soil solarization and biosolarization (experiments 1 and 2), the collected soil was filled into 400 µm-thick, 50 × 70 cm transparent polyethylene bags, with 5 L of soil per bag. For experiment 2, tomato residues, predominantly stems and fresh leaves, were obtained from the same greenhouse (Rosella Ltd) by the end of the previous cropping season. The above-ground plant material was cut into small pieces (2–4 cm) (Zanón et al., 2011) and mixed with the soil in four doses: 0, 10, 30, and 100 g L^{-1} soil, equivalent to 0, 2, 6, and 20 kg m^{-2}, respectively, in the field. Four replications (plastic bags with or without organic amendment) were prepared for each treatment (Tables 1 and 2). Tap water was added to the soils to achieve approximately 75% of the water-holding capacity. The bags were tightly closed using a heat-sealing packaging machine or self-adhesive packing tape. Solarized and biosolarized bags were placed horizontally on glasshouse benches, forming a soil layer approximately 10 cm thick in each bag, and exposed to the sun for varying periods of solar heating (7, 14, 21, or 30 days). All treatments were performed during the hottest months of the year, late June to July. Untreated controls were similarly prepared but remained open, and together with bags filled with organically amended non-solarized soils, were placed on shaded glasshouse benches. Four replications were used for each treatment, and the treatments were arranged in a randomized complete block design.

Soil temperatures were recorded at a depth of 5 cm using a hand-held soil thermometer to the nearest 0.1°C. Three measurements were made daily at 09:00, 12:00, and 15:00 hours. Soil temperature ranged from 42.0 to 49.2°C in solar-treated soils and from 28.3 to 32.5°C in the shaded, non-solarized bags.

Disease severity and effectiveness of the soil treatments

To evaluate the effectiveness of the applied methods for controlling the crown and root disease complex of tomato, the soils were transferred to 1-L plastic pots according to the treatments. Pots were arranged in a completely randomized block design on a shaded glasshouse bench. Four high-quality tomato seeds (c. Ideal) were planted in each pot. One week after emergence, seedlings were thinned to one plant of a similar size per pot. For experiment 3, the treated soils from experiment 2 were replanted, thus producing a second successive crop of tomatoes after the applied treatments. Plants were grown in the greenhouse for 75 days, with daytime temperatures ranging from 23.8 to 33.4°C, and were manually watered twice weekly or as needed. Prior to disease severity (DS) evaluation, tomato plants were harvested from the pots, and roots were washed with tap water. Roots and lower stems were evaluated for percentage of rotted or discoloured root tissue using a 0-5 rating scale: 0 = no visible lesions on the roots, plant is healthy; 1 = traces to 25% of the root surface affected; 2 = 26–50%; 3 = 51 to 75%; 4 = 76 to 100% of the root surface discoloured or covered with necrotic lesions, plant is chlorotic and stunted; and 5 = root system completely decayed, internal crown discoloration, stem base covered with necrotic lesions, wilted or dead plant, for each treatment disease index was calculated as an average value of disease severity assessed on roots and lower stems of all the evaluated plants (Vatchev, 2016). To confirm that the disease symptoms were due to pathogens associated with the crown and root rot disease complex, isolations from symptomatic plant roots collected randomly from each treatment at the end of the experiments were routinely performed on WA, acidified PDA, and OA media.

The effectiveness (E%) of each soil treatment was calculated on the base of disease severity index values using Abbott's formula (Abbott, 1925) as follows:

$$E\% = [1 - (X/Y)]\times 100,$$

where X corresponds to the disease severity index in a treated soil and Y corresponds to the disease severity index in the untreated control soil.

Statistical analyses

Each of experiments 1 and 2 was repeated in two successive years. The independent repetitions yielded similar results. Separate analyses of each trial revealed homogeneous variance of the experimental error across repetitions; therefore, the data from the repeated trials were combined for analysis. The resulting data sets were analyzed using analysis of variance, with an F-test for the significance of the treatment means, and Least Significant Difference (LSD) values were computed at $P \leq 0.05$ (Gardiner, 1997). Where applicable, treatment means were separated by Duncan's multiple range test ($P \leq 0.05$, Duncan, 1955). Experiment 3 was repeated once with similar results. The results from a single representative experimental trial are shown. All analyses were performed with IBM SPSS Statistics version 19.0 for Windows.

Results and Discussion

Disease severity and effectiveness of the soil treatments

Experiment 1

The results presented in Table 1 clearly show a significant ($P < 0.05$) reduction in crown and root rot severity on plants grown in soils solarized for 21 and 30 days as compared to the untreated control. The application of soil solarization for 30 days yielded the best disease control. The mean effectiveness of this treatment – 40.9%, calculated according to Abbott's formula (Abbott, 1925) – was higher than the level of disease control achieved by 21 days of solarization – 27.7%. Solar heat treatments for 7 and 14 days reduced the mean values of DSI compared to the untreated control soil, but the difference was not significant.

Table 1. Effects of different periods of soil solarization on severity of crown and root rot disease complex of tomato

№	Treatment	Disease Severity Index (0–5)[a]	Level of Disease Control (%)[c]
1	Untreated shaded control	2.20 a[b]	–
2	Solarization for 7 days	1.97 a	10.5
3	Solarization for 14 days	1.92 a	12.7
4	Solarization for 21 days	1.59 b	27.7
5	Solarization for 30 days	1.30 c	40.9

$F = 2.71$; $LSD_{0.05} = 0.256$.

[a] For each treatment disease index (DSI) was calculated as an average value of disease severity (DS) assessed on 0-5 rating scale, where 0 = no visible lesions on the roots, plant is healthy and 5 = root system completely decayed, internal crown discoloration, stem base covered with necrotic lesions, wilted or dead plant.

[b] Values of disease severity index (DSI) followed by different letters are significantly different at $P \leq 0.05$ according to Duncan's multiple range test.

[c] Effectiveness (disease control level) of each treatment was calculated on the base of the disease index value using the Abbott's formula.

Experiment 2

The addition of fresh tomato residues as an organic amendment at 10 g and 30 g per liter of soil resulted in a reduction of disease severity by 20.3% and 16.3%, respectively, compared with the control; however, the effect was not statistically significant (Table 2). The highest disease severity was observed in the treatment that incorporated the highest amount (100 g) of tomato residues per liter of soil. In this treatment, the disease rating was significantly higher by 44.5% than that recorded in the untreated control. Like the previous experiment, soil solarization alone, after 30 days, resulted in a significant reduction of root and crown rot disease severity by 37.3% compared to non-solarized, non-amended soil. Higher disease control levels were recorded in each treatment that received fresh organic amendment, followed by 30 days of solar heating. Disease index values were reduced by 44.9% to 52.5%, yet were not statistically different from those in the treatment with solarization alone. Nevertheless, the best result among the tested alternatives was obtained after applying 100 g of tomato residues per liter of soil, combined with solarization.

Table 2. Effects of organic amendments, soil solarization and combinations of both on severity of crown and root rot disease on complex of tomato

№	Treatment	Disease Severity Index (0–5)[a]	Level of Disease Control (%)[c]
1	Untreated control	2.63 b[b]	–
2	Tomato residues 10 g L^{-1} soil (2 kg m^{-2})	2.15 b	20.2
3	Tomato residues 30 g L^{-1} soil (6 kg m^{-2})	2.20 b	16.3
4	Tomato residues 100 g L^{-1} soil (20 kg m^{-2})	3.80 a	-44.5
5	Solarization for 30 days	1.65 c	37.3
6	Tomato residues 10 g L^{-1} soil (2 kg m^{-2}) + Solarization for 30 days	1.27 c	51.7
7	Tomato residues 30 g L^{-1} soil (6 kg m^{-2}) + Solarization for 30 days	1.45 c	44.9
8	Tomato residues 100 g L^{-1} soil (20 kg m^{-2}) + Solarization for 30 days	1.25 c	52.5

$F = 10.61$; $LSD_{0.05} = 0.49$.

[a] For each treatment disease index (DSI) was calculated as an average value of disease severity (DS) assessed on 0-5 rating scale, where 0 = no visible lesions on the roots, plant is healthy and 5 = root system completely decayed, internal crown discoloration, stem base covered with necrotic lesions, wilted or dead plant.

[b] Values of disease severity index (DSI) followed by different letters are significantly different at $P \leq 0.05$ according to Duncan's multiple range test.

[c] Effectiveness (disease control level) of each treatment was calculated on the base of the disease index value using the Abbott's formula. Minus sign indicates a higher disease severity index compared to the untreated control.

Experiment 3

High levels of the crown and root rot, comparable with those in the untreated control, were observed at the end of the second cultivation of tomato plants in all treated soils (Table 3). Disease severity ratings on roots and basal stems of plants grown in non-solarized amended soils and non-amended solarized soils did not differ statistically from those recorded in the control soil, whether amended or solarized. A statistically significant reduction in disease severity ratings – from 12.7% to 16.7% – was still demonstrated in the biosolarized soils.

Table 3. Effects of organic amendments, soil solarization and combinations of both on severity of crown and root rot disease complex in the second successive cultivation of tomato plants

№	Treatment	Disease Severity Index (0–5)[a]	Level of Disease Control (%)[c]
1	Untreated control	3.78 a[b]	–
2	Tomato residues 10 g L^{-1} soil (2 kg m^{-2})	3.81 a	-0.8
3	Tomato residues 30 g L^{-1} soil (6 kg m^{-2})	3.75 a	0.8
4	Tomato residues 100 g L^{-1} soil (20 kg m^{-2})	3.89 a	-2.9
5	Solarization for 30 days	3.74 a	1.1
6	Tomato residues 10 g L^{-1} soil (2 kg m^{-2}) + Solarization for 30 days	3.30 b	12.7
7	Tomato residues 30 g L^{-1} soil (6 kg m^{-2}) + Solarization for 30 days	3.21 b	15.1
8	Tomato residues 100 g L^{-1} soil (20 kg m^{-2}) + Solarization for 30 days	3.15 b	16.7

F = 8.88; $LSD_{0.05}$ = 0.158. Experiment 3 was repeated once with similar results. Since no considerable reduction of the disease was obtained, results from a single representative experimental trial are shown.

[a] For each treatment disease index (DSI) was calculated as an average value of disease severity (DS) assessed on 0-5 rating scale, where 0 = no visible lesions on the roots, plant is healthy and 5 = root system completely decayed, internal crown discoloration, stem base covered with necrotic lesions, wilted or dead plant.

[b] Values of disease severity index (DSI) followed by different letters are significantly different at $P \leq 0.05$ according to Duncan's multiple range test.

[c] Effectiveness (disease control level) of each treatment was calculated on the base of the disease index value using the Abbott's formula. Minus sign indicates a higher disease severity index compared to the untreated control.

The results from this study showed a promising potential of soil solarization and soil biosolarization, the latter combining solarization and incorporation of fresh tomato residues, for the control of crown and root disease complex of tomato in soils "locked in" a hysteretic performance of repeated pathogen-eradicative treatments with broad-spectrum fumigants or steam heating. Both disinfestation methods provided a substantial, although incomplete (partial) disease control in potted tomato plants cultivated in heavily infested, hysteretic soils. These soils have been preliminarily subjected to solar heating in tightly closed plastic bags with or without tomato residues mixed into the soil. The disease control rates in pathogens-infested soils subjected to solarization alone increased significantly with the increase in the treatment period. The control rates reached approximately 40% in the soil that received 30 days of exposure to solar radiation. In all experiments, biosolarization provided higher disease control compared to solarization alone in all comparable treatments. The highest reduction of crown and root rot symptoms (by 52.5%) was achieved in soil receiving the maximum amount of tomato residues – 100 g L^{-1} soil and then subjected to 30 days of solarization. The levels of disease control observed in all biosolarized soils were statistically similar regardless of the amount of fresh tomato residues incorporated in the infested soil prior to the solarization process.

Our results are by numerous studies which have demonstrated that pre-plant soil solarization both alone or in combination with incorporated raw or composted organic matter, the so called "biosolarization" (Stapleton et al., 2016; Birthisel et al., 2019), significantly reduces soilborne diseases of tomatoes caused either by individual plant pathogens (Ioannou, 2000; Klein et al., 2007; Katan, 2010; Vitale et al., 2011; McGovern, 2015) or complex infections caused by multiple fungal species (Tjamos et al., 1999; Tsitsigiannis et al., 2008; Klein et al., 2011; Lombardo et al., 2012; Testen and Miller, 2018; Testen et al., 2021; Jabnoun-Khiareddine, 2019) and Oomycetes (D'Addabbo et al., 2010; De Corato et al., 2011) or plant parasitic nematodes (Klein et al., 2012). Widely deployed in modern agroecosystems, soil solarization has proven to be ecologically sound (Gamliel and Katan, 2009; Gilardi et al., 2014; Panth et al., 2020) and an economically attractive pre-planting soil disinfestation method (Yaron et al., 1991; Hasing et al., 2004). Solarization is also technologically feasible, compatible with other plant protection strategies, and suitable for integrated pest management programs (Katan and Gamliel, 2010; Kumar et al., 2017). The treatment effects comprise hydrothermal and biological processes in moist soil covered with transparent polyethylene film and exposed to solar radiation (D'Addabbo et al., 2010). The penetrating solar energy trapped in topsoil generates temperatures that are lethal or sublethal to fungal and bacterial plant pathogens (Davis, 1991), phytoparasitic nematodes (Stapleton and Heald, 1991; Klein et al., 2012), insects, and weed seeds (Elmore, 1991; Santos et al., 2006).

A few studies have been conducted to date to investigate the potential of tomato crop residues as a carbon source for biosolarization. Zanón and Jordá (2008) successfully eradicated *Clavibacter michiganensis* subsp. *michiganensis* by incorporating tomato crop residues into growth substrate (mixture of peat moss and sand), followed by a four-week treatment at a constant temperature of 45ºC. Similarly, *Ralstonia solanacearum* was not detected in the growing medium after six-week treatment at the same conditions (Zanón et al., 2011). Biosolarization using tomato plant debris as a fertilizer positively influenced the yield and fruit quality of greenhouse-grown tomatoes (García-Raya et al., 2019). However, no aspects of plant health were evaluated in the study. Similarly, Mitidieri et al. (2021) effectively controlled a range of soilborne fungal pathogens and nematodes in greenhouse tomato by repeated treatments with soil solarization and biofumigation, the latter utilizing tomato crop residues. In addition to solar heating and anaerobic soil conditions, accumulation of volatile toxic compounds, including alcohols, aliphatic disulfides, aldehydes and organic acids, which can lower soil pH and together with reversible, yet relatively stable shifts in the structure of soil microbial community towards antagonistic anaerobic bacteria and fungi may affect survival of pathogenic organisms and increase the general soil suppressiveness (Momma, 2008; Rosskopf et al., 2015; Van Bruggen et al., 2016; Yang et al., 2021). Results from this work and the literature suggest that soil solarization and biofumigation could be used as singular disease control measures; however, they might require annual soil disinfestations to be performed before each crop cycle. It will also be recommended for the future to optimize their effectiveness by combining disinfestation procedures with other compatible control strategies. In the present study, the use of fresh tomato crop residues as a soil amendment, without subsequent solar heating, had no statistically discernible impact on disease reduction. When incorporated at lower rates, tomato residues had little or no inhibitory effect on the disease. Moreover, when the highest amount of residues (100 g L^{-1} soil, equivalent to 20 kg m^{-2} or 200 t ha^{-1}) was incorporated into disease-infested soil, a significant increase in crown and root rot was observed. The most likely explanation is that the causal pathogens, being also opportunistic or saprophytic colonizers, had taken advantage of the free physical niche and food source provided by the fresh plant residues (Whipps, 1997) or due to an increased saprophytic reproduction where crop residues are not buried by deep ploughing (Dixon and Tilston, 2010). Indeed, that amount of aboveground tomato vegetative mass could hardly be achieved per unit area in tomato cultivation. Piedra Buena (2006) reported that the tomato crop could provide up to 110 t ha^{-1} (11 kg m^{-2}), which is significantly less than the maximum dose used in our experiments. Incorporation of tomato green residues from the previous crop alone may not be consistently effective for controlling crown and root rot. For effective disease management, it must be combined with airtight coverage of the soil for at least 30 days and, if possible, should coincide with the warmest period of the year.

A purpose of this study was also to determine the possible long-term follow-up effects of solarization and biosolarization on hysteretic soil on crown and root rot of tomato. Unlike previous research, which showed that the effects of solarization and biofumigation last more than one year (Özaslan et al., 2015), in this study, neither the effect of solarization nor that of biofumigation lasted to the next cultivation round under the specific conditions described here. Indeed, in the second successive crop of tomatoes following the application of alternative treatments, a statistically significant reduction in the disease was found in the biosolarized soils. However, this treatment effect was too low to justify further data collection.

The effects of the application of organic amendments with solarization, also known as "biosolarization", "biofumigation" or "biodisinfection" (Paulitz and Belanger, 2001; Rosskopf et al., 2015), etc., on physical, chemical, and biological characteristics of soil and the mechanisms that contribute to the disinfestation process are not yet fully understood and require further investigation. Recent studies have highlighted the importance of environmental conditions and technical variables that must be considered during the constant process of solar heating, so as to prevent rapid oxygen depletion and maintain sub-lethal temperatures and low oxidation-reduction potential levels for the duration of the treatment (Block et al., 2000). Also, here are included specific characteristics of plastic films (Katan and Gamliel, 2010; Gamliel and van Bruggen, 2016), high soil moisture content of airtight covered soil (Stapleton, 2000; Momma et al., 2013), type and amount of the organic materials or species of the crop whose residues are added to the treated soil (Di Gioia et al., 2017; Liu et al., 2019), size of fragments incorporated, depth and distribution in soil (Gamliel and van Bruggen, 2016), etc. These aspects are out of the scope of this work. Unquestionably, both soil disinfestation methods studied here represent different, biologically based, and more eco-friendly approaches compared to biocidal fumigation or steam sterilization of soil. Further research is needed to explain the lack of a prolonged disease suppressive effect, e.g., for more than one cropping season, and to elucidate the possible role of a preliminary hysteretic condition in soil response to the application of environmentally benign disinfestation alternatives.

As can be seen from the literature review, numerous in-depth studies have examined and documented the effects of solarization or biosolarization on individual soilborne pathogens in tomatoes and many other crops. The current study is among the few that identify and potentially target the overall components of the causal pathogen complex inciting crown and root rot in greenhouse tomato, rather than focusing on individual species involved in the plant-pathogenic community. This rather holistic approach (Mannaa and Seo, 2021) would prevent the risk of the so-called "disease trading" or the change in the dominant pathogen (Kreutzer, 1960) within the disease complex – a phenomenon that inadequate species-specific disease control efforts might bring about. Furthermore, targeting all co-existing pathogenic species that may interact and shape pathogen community structures in the field (Fang et al., 2021) is, in my view, likely to be the only feasible manner that can provide a realistic assessment of the effectiveness of the employed disease control strategies. The concept of a multiple or multicomponent etiology of certain complex plant diseases and disorders, resulting from simultaneous infections of the same host plant by two or more pathogen species, is not new. Complex etiological considerations were first published in 1931 by Fawcett (Fawcett, 1931), who urged plant pathologists to conduct experimentation with known associations of pathogens. This concept has been further elaborated under different terms and implemented by Stakman (1964), Powell (1971), Wallace (1978), but only in the recent years has been brought into sharp focus by the publications of Khan and Dasgupta (1993), Mazzola (1998), Le May et al. (2009), Tewoldemedhin et al. (2011), Lamichhane and Venturi (2015), Wheeler et al. (2019), Wolfgang et al. (2019), Mazzola et al. (2020), Zitnick-Anderson et al. (2020), Bozoğlu et al. (2022) and many others, giving rise to a transition of Plant Pathology from the "one pathogen-one disease hypothesis" to the "pathobiome paradigm" (Mannaa and Seo, 2021).

Repetitive soil eradicative disinfestation practices, which involve the use of highly toxic, broad-spectrum chemical fumigants or heat steaming at nearly 100°C, are a drastic, often annually recurring pulse disturbance (Holling, 1973; Shade et al., 2012) to the structure and functional activity of soil microbial communities. The microbial ecology literature encompasses several concepts that may be closely related to soil disinfestation as a source of direct disturbance to the soil microbial environment and its buffering capacity. The latter is also defined as the soil's resilience to biological stress (Szabolcs, 1994). The concept of biological buffering capacity has been summarized by Seybold et al. (1999), Blanco and Lal (2008), and others as the ability of soil (ecosystem) to resist and absorb perturbations, as well as the ability to restore itself and to recover its functional and structural integrity after disturbance. Simultaneously, in the scientific literature, this definition has been split into two terms that account for the "resistance" and the "resilience" of soil microbiota. These occur most often and can serve as categories for the impact of disinfestation procedures on the soil ecosystem and its functions, such as the response to plant pathogen (re-) invasion and disease suppressive potential. From Holling (1973) and Pimm (1984) via Szabolcs (1994) and many others to the present day (Gullino et al., 2022; Smith et al., 2022), ecosystem resistance and resilience have been defined in different ways and from different perspectives, primarily conceptually rather than experientially. Resistance is generally defined as the inherent capacity of the system to withstand disturbance, whereas the term resilience applies to a "self-healing" capacity of an ecosystem after perturbation (Kibblewhite et al., 2008). Resilience has also been referred to as the capacity to maintain or recover its functional and structural integrity in response to adverse changes and disturbances or to bounce back to its original state after a disturbance (Pimm, 1984; Seybold et al., 1999; Shade et al., 2012; Ludwig et al., 2018). Further specifications on the definition of "resilience" have been provided by again splitting the term into "engineering resilience" and "ecological resilience", for which even more specific and precise definitions have been proposed by Martin et al. (2019). No matter which definitions we choose to stick with, the multiple pulse (short-term) disturbance to the soil ecosystem (sourced by recurrent soil fumigation and steam sterilization) irreversibly reduces or eliminates biological factors that confer the benefits of disease suppression, thus permanently rendering the soil highly conducive to crown and root rot of greenhouse tomato. Moreover, based on this fact, I argue that the resistance or counteractive capacity of the soil microbiome to function as an environmental buffer against soilborne plant pathogens is compromised to the point of insufficient recovery. Similarly, the resilience of soil microbial communities is evident, as no recovery process, whether faster or slower (Seybold et al., 1999; Shade et al., 2012), of biologically based disease suppression, whether general or specific, was observed before or after the annual eradicative disinfestation treatments to the soil were terminated.

Briefly, in this article, the "hysteresis behaviour" is referred to a destroyed soil resistance, meaning (1) an eliminated counteractive capacity of soil microbiome to function as an environmental buffer against reinvasion and rapid build-up of plant pathogenic populations in treated soil and

(2) a compromised resilience or inability of soil microbial communities to recover their disease suppressive capacity. Both are regarded as a result of multiple pulse disturbances caused by the application of recurring pathogen-eradicative treatments to soil. It is worth noting that more diverse systems are considered more resilient to both natural and anthropogenic perturbations (Kibblewhite et al., 2008). To exacerbate the conditions for greenhouse soils, the recurrent pulse disturbance (resulting from drastic soil treatments) has been combined with and complemented by antecedent press or long-term disturbance (Shade et al., 2012). The latter was caused by the introduction of agriculture itself and, more importantly, by the industrial greenhouse operation as a source of continuous environmental stress and substantial changes in soil microbial communities. Repeated soil disturbances without sufficient recovery imply a hysteretic condition in the soil microbiota, which typically follows ecosystem degradation (Seybold et al., 1999; Grandy et al., 2012). This condition was observed in dozens of tomato-producing greenhouses across the country; all had received recurring treatments with broad-spectrum biocides (chemical fumigants or steam heating) in the years preceding the observation (Vatchev, 2004, 2016; Yanashkov and Vatchev, 2020). Seybold et al. (1997) described a similar, although hypothetical, hysteresis behavior model associated with the loss of soil capacity to recover ("hysteric manner" of soil recovery) resulting from the annual experience of disturbance following the application of a particular cropping system on the same land.

Consistent with previous research (Seybold et al., 1999; Scheffer et al., 2001; Wilson and Tisdell, 2001; Grandy et al., 2012; Song et al., 2015), this study hypothesized that substitution of broad-spectrum eradicative approaches for more ecologically benign soil disinfestation practices can disrupt the tendency towards re-creating patterns of hysteresis within soil microbiome in response to recurrent disturbances by chemical or physical sterilization treatments. The study's findings demonstrated that, in contrast to chemical fumigation and steam heating, which aim to kill or eliminate soilborne pathogens from the soil, the application of soil solarization or biofumigation significantly reduced disease severity ratings of the crown and root rot disease complex in tomato plants grown in heavily infested soil. This shift in disease response was attributed to the less harmful effect on non-target soil microorganisms. As the same soil had previously exhibited hysteresis behavior in terms of disease control failure due to drastic soil disinfestation, our results indicated that these disinfestation approaches, with a milder effect, managed to change the tendency of the boomerang effect on disease development following drastic pre-plant soil disinfestations and thus overcome the condition of hysteresis in the soil. Further research is needed to elucidate whether the disease control effect resulted from a temporary reduction in soil inoculum potential or some recovery of microbial buffering capacity, as referred to in soil disease suppression. Indeed, in this study, only partial or incomplete disease control of the crown and root rot disease complex of tomato was observed after single solarization or biosolarization treatment of the pathogen-infested soil, showing hysteresis. Additionally, the positive disease control response was limited to the first cropping round, and disease reduction was not evident in the subsequent tomato crop. Previous publications have covered potential advantages of regular applications of biologically based soil disinfestation approaches (Klein et al., 2012), alone or in integration with other appropriate disease control strategies that might further improve the results from the pre-plant disinfestation treatments (Vatchev, 2004; Minuto et al., 2006; Jabnoun-Khiareddine et al., 2019).

Conclusions

Soil solarization and biofumigation have proven to be effective and sustainable methods for controlling various soilborne diseases in a range of protected and outdoor crops. They are fully compatible with soil-based tomato cultivation systems in greenhouses. As demonstrated in this paper, the two disinfestation alternatives efficiently reduce the crown and root rot disease complex of tomato under conditions of hysteretic, heavily infested soil, which has repeatedly received drastic pathogen-eradicative treatments in the past with no positive effect on disease prevention and control. Hence, solarization, either alone or in combination with fresh tomato residues added to the soil prior to solar heating, could be successfully applied to control root and lower stem rots of tomatoes caused by a wide range of fungal and fungal-like necrotrophic pathogens under the described conditions of hysteresis or less extreme soil conditions.

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