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AN EVALUATION OF IMPROVED POLYETHYLENE FILMS FOR COOL-SEASON SOIL SOLARIZATION

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Abstract. **The utility of soil solarization under Florida's hot, cloudy, and rainy summer climate has been previously demonstrated, and solarization has been shown to be a potential alternative to methyl bromide for fall production of tomato (*Lycopersicon esculentum*). Because most of the tomatoes are grown in late winter and spring, it was pertinent to investigate whether improved polyethylene films would also permit cool-season soil solarization by enhancing soil heating and reducing energy losses from the soil. In Gainesville in spring 1996, a 150 μm (6 mil) infrared-absorbing (IR) thermal film overlying bubble film resulted in higher maximum and minimum soil temperatures than a 20 μm (0.8 mil) clear low density polyethylene (LDPE) film. In the spring of 1997, soil solarization experiments were conducted in Bradenton and Gainesville. At Bradenton, 100 μm-thick IR film was installed on 19 Dec. 1996, 2 Jan. 1997 and 17 Jan. 1997 to give durations of 5, 7, and 9 weeks of solarization. UV-stabilized bubble film was also installed for the 9-week duration only. An 8-week solarization period was initiated at Gainesville on 23 Jan. 1997 and included the following polyethylene films: 50 (2 mil), 75 (3 mil), and 100 μm-thick (4 mil) IR film, UV-stabilized bubble film, black film, and a 19 μm-thick (0.75 mil) clear high density polyethylene (HDPE) film. The specialty films increased soil temperatures during cool-season solarization at both sites. However, lethal temperatures were not achieved by any solarization treatment as indicated by the emergence of annual weeds that are commonly controlled by summer solarization. The results of winter solarization at two Florida sites were not encouraging for use of soil solarization for weed control in cool-season crop production.**

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The impending loss of methyl bromide as a soil fumigant is expected to have a negative impact on Florida's horticulture industry unless adequate alternatives can be identified. In 1976, Katan et al. described a process of soil disinfestation that used transparent polyethylene sheets to enhance soil heating. The technique, now commonly called soil solarization, can be effectively implemented in arid climates with abundant cloud-free, hot weather. As early as 1980, research was initiated in Florida to evaluate soil solarization for preplant pest management in tomato (Overman, 1985).

Soil solarization in summer months has been effective against a variety of plant pathogenic nematodes, soil-borne pathogens and weeds in north, central, and southern Florida. Suppression of nutsedges (*Cyperus* spp.) has been demonstrated during summer months (Chellemi et al., 1997; McSorley and Parrado, 1986; Overman and Jones, 1986). In the summer of 1996, a solarization period of 5 weeks did not suppress nutsedge as effectively as 6- and 8-week solarization periods (Chase et al., unpublished). Therefore, the duration of solarization was considered an important aspect requiring further investigation.

Horowitz et al. (1983) attributed weed control by solarization to foliar scorching of plants under the plastic mulch and decreased weed emergence after the mulch is removed. Based on this and our observations, we proposed that nutsedge suppression by solarization is due to direct kill of nutsedge tubers in soil layers where lethal temperatures occur, and indirectly by tuber depletion when alternating sprouting and shoot scorching occurs at the soil:plastic interface (Chase et al., 1997). Therefore, it was anticipated that a longer duration of solarization would result in better nutsedge control due to tuber depletion. With shorter durations of solarization, a greater number of viable tubers would remain in the soil.

Previous solarization studies in Florida have all been conducted during the summer for a fall crop. Because a spring tomato crop is most often produced, it was pertinent to investigate the possibility of cool-season soil solarization. The current study included a preliminary experiment, the objective of which was to evaluate various clear polyethylene films for improved soil heating properties. The objectives in subsequent experiments at two sites were to: (1) investigate the influence of the duration of film application on solarization efficacy; (2) determine whether thinner infrared-absorbing (IR) films are as effective in soil heating and nutsedge control as 100 μm (4 mil) IR film; and (3) evaluate the effect of soil solarization in combination with a nematicide on tomato yield.

Materials and Methods

Preplant soil solarization during the cool-season was evaluated for spring tomato production in Gainesville in 1996, and in 1997 at Gainesville and Bradenton. At the end of the solarization period, the solarization films were retained as a production mulch. Row orientation was north-south in all of the experiments.

Experiment 1 (Gainesville, 1996)

A preliminary experiment was conducted at Gainesville in spring of 1996 to explore whether improved transparent polyethylene films could extend the application of soil solarization to a spring tomato crop. Soil preparation consisted of disking-in the rye cover crop and forming rows. Preplant fertilizer N-P-K 10-10-10 was applied at 840 kg·ha^{-1} to the bed top, and was incorporated and beds formed with a 0.9 m-wide bed press. The rest of the fertilizer (144 N-130 K kg·ha^{-1} as NH_4NO_3 and KCl) was applied through the drip irrigation system in ten weekly applications, after transplanting. Three solarization treatments were installed on 28 Feb., a 20 µm-thick clear low-density polyethylene film (LDPE); a 150 µm-thick (6 mil) thermal-infrared-absorbing film (IR6M) (AT Plastics Inc., Edmonton, Alberta) alone; and the 150 µm-thick thermal-infrared-absorbing film overlying 0.9 m wide bubble film. For comparison methyl bromide-chloropicrin formulations 98:2 and 67:33 were applied at 450 kg·ha^{-1} and 390 kg·ha^{-1}, respectively. Black polyethylene mulch was applied to the methyl bromide-treated plots as well as to an untreated check.

Soil temperature was measured at 10-minute intervals at the soil surface, 5, 10, and 25 cm deep in the soil using a CR10 datalogger (Campbell Scientific, Inc., Logan, Utah). Copper-constantan thermocouples were inserted 0.45 m from the edge of the bed. Temperatures were measured for 1 bare (nonmulched) area between two plots, 1 replication of the 20 µm-thick LDPE, 1 replication of the 150 µm-thick IR6M, and 2 replications of the IR6M/bubble combination. The experimental design was a randomized complete-block design with five replications. After 1 month of solarization, tomato transplants (cv. Agriset 761) were set on 28 Mar. Tomatoes were harvested on two occasions 12 and 13.5 weeks after transplanting, graded, and marketable yields were determined.

Experiment 2 (Bradenton, 1997)

At Bradenton, 100 µm-thick (4 mil) infrared-absorbing thermal clear film (IR4M) (AT Plastics Inc., Edmonton, Alberta) was installed on 19 Dec. 1996, 2 Jan. 1997, and 17 Jan. 1997 to give durations of 9, 7, and 5 weeks of solarization, respectively. Ultraviolet-stabilized bubble film (AstroCell Bubble, 1 cm diameter bubbles, 3.2 mm thickness) (Astro-Valcour, Inc., Glen Falls, New York) was also installed for the 9-week duration. Additional treatments included a nontreated check and a methyl bromide:chloropicrin-treated check (67:33 at 390 kg·ha^{-1}), both of which were mulched with black polyethylene on 17 Jan. 1997. Prior to the film applications on 17 Jan. 1997, paraquat was sprayed on 14 Jan. 1997 for weed control.

The experimental design was a randomized complete-block design with five replications. The beds were 9 m long and 0.9 m wide on 1.8 m centers. The tomato cultivar was 'Sun Pride'. Ten transplants per bed were set at an intrarow spacing of 0.6 m. Soil temperatures were measured at 30-min intervals under at the soil surface, 5, 10, and 25 cm deep in the soil using a CR10 datalogger equipped with copper-constantan thermocouples. There were three replicate measurements for each film type and depth. Tomatoes were harvested twice, graded, and marketable yields were determined.

Experiment 3 (Gainesville, 1997)

Thermal-infrared-absorbing films of various thicknesses (50, 75, and 100 µm) were compared with a high-density clear polyethylene (HDPE) film (19 µm) (Sonoco, Hartsville, SC), and a UV-stabilized bubble film for their effects on soil temperature. Solarization treatments were fumigated with 168 liters·ha^{-1} 1,3 dichloropropene (1, 3-D) or 235 liters·ha^{-1} 1,3-D + 17% chloropicrin (C-17) for the control of root knot nematode. C-17 was shown to be as effective as MBC in controlling root knot nematode (Locascio et al., 1997). The solarization treatments were compared with a nontreated check mulched with black polyethylene, and black-mulched treatments fumigated with MBC 67:33 at 390 kg·ha^{-1}, C-17 at 235 liters·ha^{-1} and 1,3-D at 168 liters·ha^{-1}. These treatments were applied on 3 Mar. 1997, two weeks before transplanting. Prior to fumigation, the plots were covered by black polyethylene mulch primarily to protect the fertilizer from leaching. Oxamyl (Vydate, E.I. du Pont de Nemours & Co., Wilmington, DE) was evaluated as an alternative to 1,3-D. It was applied as at 4.7 liters·ha^{-1} Vydate on 2, 16, and 30 April and 14 and 28 May, through the drip irrigation system. The treatments were arranged in a randomized complete-block with five replications.

Soil temperatures were measured at half-hour intervals at the soil surface, 5, 10, and 25 cm soil depths, using a Campbell CR10 datalogger outfitted with differential thermocouples. Two replicate temperature measurements were made for all films at each depth, with the exception of the black film, which had a single replication. Plots were 11 m long and 0.9 m wide. The tomato fruits were harvested and graded three times and total marketable yields were determined.

Temperature data were summarized to obtain the mean daily maximum for each film type. Analysis of variance was conducted on the yield data and the Duncan's New Multiple Range Test was used for mean separation. The level of significance was 5%.

Results and Discussion

Gainesville, 1996

In the preliminary experiment in spring 1996, the highest soil temperatures were at the soil surface and decreased with depth (Table 1). Soil solarization treatments resulted in markedly higher maximum soil temperatures than nonmulched soil and conventional black polyethylene mulch. The highest soil temperatures were recorded under the combination of the IR6M film overlying bubble film.

There was a trend towards higher marketable yields by tomato plants with the MBC treatments, which was not statisti-

Table 1. Soil temperatures at Gainesville from day 74 to day 87 in Spring 1996.

	Mean daily maximum temperature (°C)			
	Soil depth			
Film	Surface	5 cm	10 cm	25 cm
Bare soil	32.7	25.7	23.2	19.4
Black[z]	33.8	28.5	25.7	20.7
Clear[y]	48.8	35.8	31.8	23.7
IR6M[x]	45.4	34.5	30.8	23.0
IR6M-bubble[w]	51.1	37.4	32.5	24.8

[z]Black film was 38 µm low density polyethylene (LDPE), 1 replicate.
[y]Clear film was 20 µm transparent LDPE, 1 replicate.
[x]IR6M film was 150 µm infrared-absorbing LDPE, 1 replicate.
[w]IR6M-bubble was IR6M overlying 0.9 m wide bubble film, avg. of 2 replicates.

Table 2. Effect of cool-season soil solarization on marketable yield of tomatoes at Gainesville in Spring 1996.

	Marketable fruit yield	
Treatment[z]	(No. × 1000)	($t \cdot ha^{-1}$)
Black check	291.8	58.2
Black MBC 98:2[y]	322.6	61.5
Black MBC 67:33[x]	349.2	69.2
Clear	289.3	53.5
IR6M	303.0	60.6
IR6M-bubble	262.9	54.6
Significance	ns	ns

[z]Black film was 38 μm low density polyethylene (LDPE), clear film was 20 μm transparent LDPE, IR6M film was 150 μm infrared-absorbing LDPE, and IR6M-bubble was IR6M overlying 0.9 m wide bubble film.
[y]Soil treated with methyl bromide - chloropicrin 98:2 at 450 $kg \cdot ha^{-1}$.
[x]Soil treated with methyl bromide - chloropicrin 67:33 at 390 $kg \cdot ha^{-1}$.

Table 4. Effect of cool-season soil solarization on marketable yield of tomatoes at Bradenton in Spring 1997.

		Marketable fruit yield	
Treatment[z]	Duration (weeks)	(No. × 1000)	($t \cdot ha^{-1}$)
Black check	5	510.8 a[y]	98.0 a
Black MBC[x]	5	489.2 a	94.4 a
IR4M	5	442.7 a	82.6 a
IR4M	7	313.6 b	54.3 b
IR4M	9	311.8 b	59.3 b
UV-bubble	9	277.8 b	45.9 b

[z]Black film was 38 μm low density polyethylene (LDPE); IR4M film was 100 μm infrared-absorbing LDPE; and UV-bubble was ultraviolet-stabilized bubble film.
[y]Mean separation in columns by Duncan's new multiple range test, 5% level.
[x]MBC: methyl bromide:chloropicrin 67:33 at 390 $kg \cdot ha^{-1}$.

cally significant (Table 2). This may have been primarily due to root-knot nematode control by MBC. Soil solarization controlled annual weeds and suppressed nutsedge growth, but had no effect on root injury by root-knot nematodes (data not shown). The nontreated check, with 41 nutsedge plants per square meter, had the highest nutsedge density penetrating the polyethylene mulch, and a root galling index of 4. The nutsedge densities of the methyl bromide treatments and the solarization treatments were all less than 17 plants per square meter and were not significantly different from each other ($P < 0.05$). MBC 98:2 and MBC 67:33 significantly ($P < 0.05$) reduced root galling to 1 and 0.2, respectively.

Bradenton, 1997

The focus of this experiment was to evaluate the thinner, new formulation of IR film and the new UV-stabilized double-layered bubble film; and to investigate the influence of extending the duration of solarization. At the soil surface, black polyethylene mulch resulted in higher soil temperatures than either the IR4M film or the UV-bubble film (Table 3). However, the IR4M film gave the highest mean maximum soil temperatures at 5, 10, and 25 cm depths. Although both IR4M and UV-bubble films had similar mean daily maximum temperature at the soil surface, IR4M film resulted in higher temperatures than UV-bubble at 5, 10, and 25 cm depths (Table 3). Solarization temperatures, however, never exceeded 50°C. In laboratory studies, it was found that 45°C soil temperatures for six hours per day delayed emergence and 50°C for six hours per day over a 2-week period was lethal to nutsedge tubers (Chase, unpublished data). Therefore, temperatures with these field solarization treatments were never sufficiently high to directly kill nutsedge tubers.

Table 3. Soil temperatures at Bradenton from day 354, 1996 to day 50, 1997.

	Mean daily maximum temperature (°C)[z]			
	Soil depth			
Film[y]	Surface	5 cm	10 cm	25 cm
Black	37.7	29.7	26.9	22.4
IR4M	34.8	31.4	27.5	23.1
UV-bubble	35.1	29.6	26.5	22.7

[z]Temperatures are means of 3 replicates.
[y]Black film was 38 μm low density polyethylene (LDPE); IR4M film was 100 μm infrared-absorbing LDPE; and UV-bubble was ultraviolet-stabilized bubble film.

After four weeks of solarization, there were no visible signs of weed suppression under the film with any solarization treatment. Therefore, temperatures were insufficient to cause foliar scorching and direct kill of annual weed seeds. In fact, the increased soil temperatures may have promoted weed growth. At the end of the solarization period, the greatest weed growth occurred under the IR film that had been in place for 9 weeks. Since the opaque, black film prevented a visual assessment of weed growth under the film, it was assumed that no growth occurred under the opaque film. However, in the nontreated check, opacity was not sufficient to inhibit the penetration of the black film by nutsedge rhizomes. No nutsedge shoots penetrated the black film in methyl bromide-treated plots.

The marketable yield was statistically equivalent for the black mulch treatments with MBC and without MBC (Table 4). These results infer that the pest pressure was not at a significant level. Soil solarization for 5 weeks resulted in yields equivalent to the black polyethylene treatments. Increasing the duration of solarization from 5 to 7 and 9 weeks resulted in a significant decrease in yield (Table 4). The decrease in yield can be attributed to increased weed competition, since the soil area covered by weeds under IR film increased from 17% after a 5-week solarization period to 93% following 9 weeks of solarization duration.

Table 5. Soil temperatures at Gainesville from day 25 to day 75 in Spring 1997.

	Mean daily maximum temperature (°C)[z]			
	Soil depth			
Film[y]	Surface	5 cm	10 cm	25 cm
Black	33.5	29.5	26.8	22.0
HDPE	41.0	34.1	30.5	24.0
IR2M	39.7	34.0	29.3	24.0
IR3M	38.4	33.7	29.3	24.5
IR4M	39.5	33.1	29.6	23.9
UV-bubble	37.6	32.4	28.9	23.7

[z]Temperatures are means of 2 replicates for all films except black, which had 1 replicate.
[y]Black film was 38 μm low density polyethylene (LDPE); HDPE was 19 μm high density polyethylene; IR2M was 50 μm infrared-absorbing LDPE; IR3M was 75 μm infrared-absorbing LDPE; IR4M film was 100 μm infrared-absorbing LDPE; and UV-bubble was ultraviolet-stabilized bubble film.

Table 6. Effect of cool-season soil solarization on marketable yield of tomatoes at Gainesville in Spring 1997.

Film[z]	Fumigant[y]	Marketable fruit yield	
		(No. × 1000)	(t·ha^{-1})
Black	untreated	228.6 c[x]	49.6 b
Black	MBC	300.5 a	65.0 a
Black	C-17	293.7 ab	62.4 a
IR2M	C-17	190.4 d	41.6 bcd
IR3M	C-17	207.6 cd	44.3 bcd
IR4M	C-17	206.8 cd	44.3 bcd
UV-bubble	C-17	216.4 cd	47.5 bc
HDPE	C-17	183.7 de	39.0 cde
Black	1,3-D	264.1 b	58.0 a
IR4M	1,3-D	199.4 cd	44.1 bcd
HDPE	1,3-D	154.1 e	31.5 e
IR4M	Oxamyl	185.3 de	38.3 de

[z]Black film was 38 μm low density polyethylene (LDPE); HDPE was 19 μm high density polyethylene; IR2M was 50 μm infrared-absorbing LDPE; IR3M was 75 μm infrared-absorbing LDPE; IR4M film was 100 μm infrared-absorbing LDPE; and UV-bubble was ultraviolet-stabilized bubble film.
[y]MBC = 67% methyl bromide + 33% chloropicrin at 390 kg·ha^{-1}, 1,3-D = 94% 1,3-dichloropropene at 168 liters·ha^{-1}, C-17 = 78% 1,3-D + 17% chloropicrin at 235 liters·ha^{-1}, and 24% oxamyl at 4.7 liters·ha^{-1}.
[x]Mean separation in column by Duncan's new multiple range test, 5% level.

Gainesville, 1997

In this experiment, the influence of UV-bubble film and three thicknesses of the new IR formulation on soil solarization, and the effect of including fumigants for root knot nematode control was investigated. Maximum daily temperatures at the soil surface were at least 4°C higher under solarization film than under conventional black polyethylene film. The maximum soil temperature was recorded under the HDPE film at the top three depths (Table 5).

The highest yields of marketable tomatoes resulted with the black mulch treated with MBC, 1,3-D, or C-17 (Table 6). Use of solarization treatments resulted in lower yields than those obtained with the black mulch treatments with MBC, C-17, or 1,3-D, and yields were not significantly different from that with the untreated black mulch check. The inclusion of 1,3-D under IR4M film did not improve the marketable yield. There were no differences in yield among tomatoes with the various improved films. The lowest yields resulted from plants with HDPE solarization film regardless of fumigant treatment. Since there was no increased nematode pressure, the lower yields were probably due to greater competition from the extensive weed cover that occurred under this solarization film.

Preliminary results at Gainesville in spring 1996 indicated that solarization film with improved properties of soil heating and reduction of heat loss from the soil had no detrimental effect on crop yield. After further encouraging results with improved solarization films in summer 1996 (manuscript in preparation), the evaluation of cool-season solarization was expanded in spring 1997 to include two sites, more films, and varying durations of solarization. However, soil temperatures were sublethal and weed control was poor. This resulted in reduced crop vigor and marketable yields. In conclusion, the use of various improved films with properties that reduce heat-loss from the soil did not consistently promote effective soil solarization for spring tomato production in Florida. These results confirm that although summer soil solarization is a promising alternative to MBC for fall vegetable production, soil solarization cannot be relied upon as an alternative to MBC for the production of spring vegetables.

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