Soil Solarization for the Management of *Dacus frontalis* and *Dacus ciliatus* (Diptera: Tephritidae) Pupae in Heated Cucurbit Greenhouses in Southern Tunisia[1]

Amani Ben Othmen[2,4], Sabrine Chouikhi, Ali Ben Belgacem, Mohamed Sadok Belkadhi, Kamal Nagaz, and Mohamed Braham[3]

Dryland and Oases Cropping Laboratory, Arid Regions Institute, Street El Jorf, 4119 Medenine, Tunisia

J. Entomol. Sci. 61(1): 000–000 (Month 2025)
DOI: 10.18474/JES24-109

Abstract The fruit flies *Dacus frontalis* Becker and *Dacus ciliatus* Loew (Diptera: Tephritidae) are major pests of geothermal cucurbit greenhouses in southern Tunisia, causing significant yield losses. This study evaluated soil solarization coupled with the use of geothermal water and plastic film as a sustainable pest management strategy during the fallow period when only pupae of both insects are present in the soil. Solarization with geothermal water at 60°C, combined with black or transparent plastic films as mulches, significantly reduced the number of pupae and subsequent emergence of adult fruit flies in 2021 and 2022. Solarization using black plastic film resulted in the recovery of a mean of only 1 pupa per greenhouse in 2021 and 0.677 in 2022. The mean number of pupae collected from solarization with transparent film was 4.67 pupae per greenhouse in both years. In untreated greenhouses, mean numbers of pupae were 19.3 in 2021 and 18.7 in 2022. No adults emerged from pupae in the solarized greenhouses, whereas in the untreated greenhouses emergence rates were between 43.4% and 45.1%. During the production season, black film solarization reduced fruit infestation by 20.7% (75.3 flies/kg of fruit) in 2021 and 20.3% (73.9 flies/kg of fruit) in 2022. Fruit infestation in treatments with transparent film was reduced 12.7% (63.5 flies/kg) in 2021 and 16.7% (58.1 flies/kg) in 2022. In contrast, untreated greenhouses had the highest infestation levels, with 34% infested fruits (101 flies/kg) in 2021 and 40.7% infested fruits (102 flies/kg) in 2022. These results demonstrate the potential of solarization as a viable pest management tactic and perhaps a sustainable alternative for managing *Dacus* fruit fly pests in geothermal greenhouses.

Key Words soil solarization, plastic film mulches, geothermal greenhouses, fruit fly pupae

Vegetable crops are produced on approximately 167,000 ha annually in Tunisia, involving about 90,000 farms. This sector is a key component of the country's agriculture and its high-value products, with diverse cucurbit varieties grown year-round in greenhouses and open fields. These crops produce 3.2 million t of produce annually, with melons and watermelons accounting for 15% of the export crop (GIL 2024). Despite the importance of cucurbit production, two fruit fly pests are particularly

[1]Received 6 September 2024; accepted for publication 16 January 2025.
[2]Corresponding author (email: amenibenothmen11@gmail.com).
[3]University of Sousse, Regional Research Center on Horticulture and Organic Agriculture, Chott-Mariem.Sousse, Tunisia.
[4]Affiliated with Dryland and Oases Cropping Laboratory, Arid Regions Institute, Medenine and High Agronomic Institute of Chott-Mariem, University of Sousse, Chott-Mariem, Sousse, Tunisia.

problematic: *Dacus ciliatus* Becker (Cherif et al. 2023) and *D. frontalis* Loew (Diptera: Tephritidae) (Hafsi et al. 2015). These pests cause significant damage to crops and are under quarantine in Tunisia (Hafsi et al. 2015, Harbi et al. 2022).

Dacus frontalis mainly attacks cucurbits such as zucchini (*Cucurbita pepo* L.), Armenian cucumber (*Cucumis melo* L. var. *flexuosus*), pumpkin (*Cucurbita maxima* Duchesne), watermelon (*Citrullus lanatus* [Thunberg] Matsumura & Nakai), melon (*Cucumis melo* L.), and cucumber (*Cucumis sativus* L.) (Hafsi et al. 2015). Females lay their eggs within the host fruit tissue, and larvae feed within the fruit, consuming the pulp and destroying the fruit, resulting in significant economic losses. Last instars drop to the soil to pupate (Christenson and Foote 1960, Ekesi et al. 2007, Hafsi et al. 2015, Steffens 1983). Without effective control measures, *D. frontalis* can cause up to 100% losses in cucurbit crops, especially during the dry season when attacks are most intense (Steffens 1983). Research on successful control strategies for *D. frontalis* is limited (Elghadi and Port 2019).

Only a few methods have been suggested to reduce fruit fly populations, ranging from chemical treatments to biological control and bait traps. Despite their negative environmental impact, pesticides currently dominate the methods used to control pests (Mahmud et al. 2015). *Dacus frontalis* eggs and larvae develop inside the fruit, making them relatively protected from insecticide applications, except for systemic treatments. Therefore, it is crucial to investigate more sustainable alternatives for controlling these pests. Solarization is a physical control method used before planting crops for soil pathogens, including fungi, bacteria, nematodes, weeds, and insects (Katan 1987). Although not used as frequently against insect pests (Gill and McSorley 2010), the method is useful in regions with intense solar radiation (Linke et al. 1991). It is implemented by covering the soil with plastic film to capture solar energy and increase temperature within the soil to exceed thermal limits of pest species, both in open fields and greenhouses (DeVay and Katan 1991).

In Tunisia, soil solarization is commonly used for soil sterilization (Jabnoun-Khiareddine et al. 2020). In geothermal greenhouses in Kebili in southwest Tunisia, this technique, initially developed for nematode control, has emerged as a promising alternative to chemical treatments (Hadded 2013). It leverages naturally heated geothermal water (Hachicha et al. 2012, Mohamed 2003), as irrigated soil conducts heat more effectively than dry soil, thereby increasing the susceptibility of soil-inhabiting organisms to heat (Elmore 1995).

The objective of this study was to evaluate the effectiveness of soil solarization reinforced by geothermal water heating as a sustainable method for controlling *Dacus* spp. pupae. The pupal stage was targeted because the pupae are immobile and do not move within the different strata of the soil, and the pupal stage occurs during the summer months to provide an ideal opportunity to take advantage of soil solarization to reduce pest numbers before the start of the next growing season.

Materials and Methods

Study area. The study was conducted in the Bazma region, Kebili governorate (N 33°40′45″, E 9°1′17″, altitude 64 m) in southwestern Tunisia. The region is characterized by a hyperarid desert climate. The mean annual rainfall is $<$100 mm and is highly irregular; the relative humidity does not exceed 50%. Mean temperature peaks at 32°C in July, the hottest month, and drops to 9°C in January, the coldest month (Hadded

2013). The region is dominated by an oasis-based agroecosystem with sandy to sandy-loam soils. A soil analysis was conducted at the Water and Soil Laboratory of the Arid Regions Institute, yielding a soil composition of 16% clay, 33% silt, and 47% sand, with a pH of 7.2 and an organic matter content of 0.7%.

The study was conducted in greenhouses heated by geothermal waters throughout the production season and in which Armenian cucumbers were cultivated. At the end of the season (June), the cucumber crop, infested with *Dacus* spp., was removed, and all debris was destroyed.

Experimental protocol. The experiment was conducted in nine monotunnel greenhouses of Armenian cucumbers, each covering an area of 540 m^2 (length 60 m, width 9 m) in a completely randomized block design. From July 2021 to August 2021, soil solarization was performed by 3 h of irrigation of the soil with 67–70°C geothermal water once a week, ensuring homogeneous saturation of the soil across the treated surface. This irrigation resulted in water stagnation at a depth of about 30 cm. After irrigation, the soil was covered with a 20-μm thickness of agricultural polyethylene film, either transparent (Tjamos 1991) or black (Abu-Gharbieh et al. 1991) sourced from Plastic SIPA SUD Society in Sfax, Tunisia. Each treatment was applied in three greenhouses; the other three greenhouses were used as untreated controls. In September, Armenian cucumber was planted in a monotunnel greenhouse, laid out in four rows 60 m long. The same protocol was repeated during the 2022 season under identical experimental conditions and greenhouse arrangements.

Soil temperatures were measured at 4- to 5-cm soil depth, corresponding to the pupation zone of *Dacus* spp. (Dubois et al. 2023, Susanto et al. 2022), using Delta OHM HD3910.1 probes available through Senseca in Germany. Simultaneously, a DL-TH-01 data logger distributed by Metravi Instruments in India was used to record the air temperatures. Maximum soil temperatures recorded in July reached 45°C in 2021 and 44.5°C in 2022; minimum temperatures recorded in August were 21.2°C in 2021 and 22.5°C in 2022.

Soil sampling. Soil samples were taken before and after solarization. The first sample was taken at the end of June and the second in October. Samples were collected randomly at 15 × 15 cm at a depth of 10 cm at three points arranged diagonally in each greenhouse. Pupae were then sieved from the soil and incubated in the laboratory to be counted and observed for emergence. This protocol was used in both seasons.

Fly monitoring. At the beginning of the season, during the flowering stage, three bait traps were installed in each greenhouse to monitor the number of flies emerging after solarization (Nigg et al. 2000). Traps were constructed with perforated plastic bottles half filled with mineral water (Sowmiya et al. 2021) and containing 40 g of water-soluble diammonium phosphate (Cherif et al. 2023, Hafsi et al. 2015). Yellow adhesive tape was affixed around the bottles to enhance attraction (Al-Mtarfi and Al-Shammari 2023).

Fruit infestation. This stage was assessed using the protocol modified from that of Candido et al. (2008). During the first 15 d after fruit development, the fruits were inspected to determine the number of infested fruits per greenhouse on the basis of occurrence of oviposition and exit holes, as well as the presence of larvae, as described by Hafsi et al. (2015) and Keçe et al. (2019). The number of infested

Table 1. Soil temperature in the Bazma region, Kebili, during 2021 and 2022.

		Soil Temperature (°C)					
		Control		Black		Transparent	
Year	Month	Minimal	Maximal	Minimal	Maximal	Minimal	Maximal
2021	July	24.3	44.6	28.1	54.1	27.7	52.7
	August	22	40.7	27.9	52.7	27.3	50.5
2022	July	25.5	44.4	32.6	55	31.1	54.2
	August	23	41	33.9	53.5	32	50.6

fruits was expressed as the direct counting of the number of infected fruits out of the total number of inspected fruits. Subsequently, the infested fruit was weighed and incubated in the laboratory until the flies emerged to assess the infestation rate, calculated as follows: number of flies emerged/kilogram of fruits (Rasolofoarivao et al. 2022).

Data analysis. Data were tested for normality and analyzed using RStudio software. A one-way analysis of variance was performed to compare pupal numbers, adult emergence indices, and fruit infestation rates, and means were compared using Tukey's honestly significant difference test at a 5% significance level.

Results

Soil temperature. Of the three soil treatments, the control plots recorded the lowest soil temperatures throughout the study period, with minimal values ranging between 22°C and 25.5°C and maximal values from 40.7°C to 44.6°C. Use of black film as mulch yielded the highest temperatures, with maximal values peaking at 55°C in July 2022. Minimal temperatures were also high, ranging from 27.9°C to 33.9°C. Maximum and minimum temperatures recorded in the soils covered with the transparent film ranged from 50.5°C to 54.2°C and from 27.3°C to 32°C, respectively.

When comparing soil temperatures between July and August for both years, a clear trend emerges across the three soil treatments. In unsolarized soil, July consistently recorded higher minimal and maximal temperatures than August in both 2021 and 2022. Similarly, under black and transparent films, July generally showed slightly higher temperatures than August in 2021 (54.1°C and 52.7°C) and 2022 (55C° and 54.2°C), with the differences being more marked for minimal temperatures (Table 1).

Pupae collection. Fig. 1 illustrates the effect of soil solarization achieved through geothermal irrigation and covering the soil with black or transparent polyethylene film on the number of *Dacus* pupae during the 2021 and 2022 seasons. Before solarization, the initial number of pupae was significantly higher in solarized greenhouses compared with unsolarized greenhouses. Soil solarization significantly reduced pupal numbers in soil covered with black or transparent plastic film compared with unsolarized soil, both in 2021 ($F = 508.2$, df $= 2$, $P < 0.001$) and

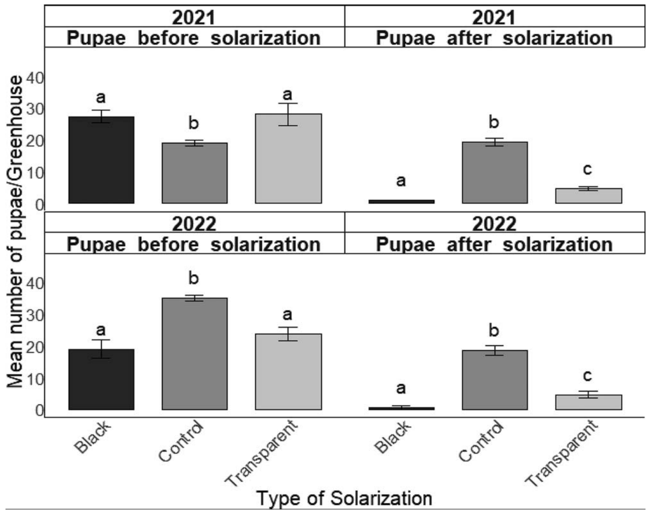

Fig. 1. Mean number of collected pupae per greenhouse for the black, transparent, and control soil solarization treatments at two times, before and after solarization, during 2021 and 2022.

2022 ($F = 201$, df $= 2$, $P < 0.001$). The black plastic film was more effective, achieving a significant reduction in the mean number of pupae (1 $\pm$ 0 in 2021 and 0.677 $\pm$ 0.577 in 2022) compared with the transparent plastic film (4.67 $\pm$ 0.577 in 2021 and 4.67 $\pm$ 1.15 in 2022). In contrast, unsolarized greenhouses recorded the highest number of pupae (19.3 $\pm$ 1.15 in 2021 and 18.7 $\pm$ 1.53 in 2022). Additionally, before solarization for the second year (2022), a significant difference was observed between the unsolarized greenhouses and those solarized before the 2021 season (Fig. 1).

Fig. 2 presents the emergence rates of adult flies from pupae collected before and after soil solarization with black or transparent polyethylene film during the 2021 and 2022 seasons. Before solarization, emergence rates were high across all greenhouses, with no significant differences observed. However, after solarization, a substantial reduction in adult fly emergence was noted in greenhouse soils covered with black or transparent film compared with uncovered control greenhouses. In 2021, the emergence rates were significantly lower in greenhouses solarized with black or transparent film than in control greenhouses ($F = 15.7$, df $=$ 2, $P = 0.0041$). Similarly, in 2022, solarized greenhouses exhibited significantly reduced emergence rates compared with the control ($F = 5.15$, df $= 2$, $P =$ 0.0049). No adult flies emerged from pupae collected in solarized greenhouses treated with black or transparent film in both years, except for a single deformed individual that failed to complete its emergence. In contrast, control greenhouses recorded the highest emergence rates, reaching 45.1% $\pm$ 29.6% in 2021 and 43.4% $\pm$ 19.0% in 2022 (Fig. 2).

Fly monitoring. After the 2021 soil solarization, the mean number of flies captured in greenhouses with soils covered with transparent or black plastic films was

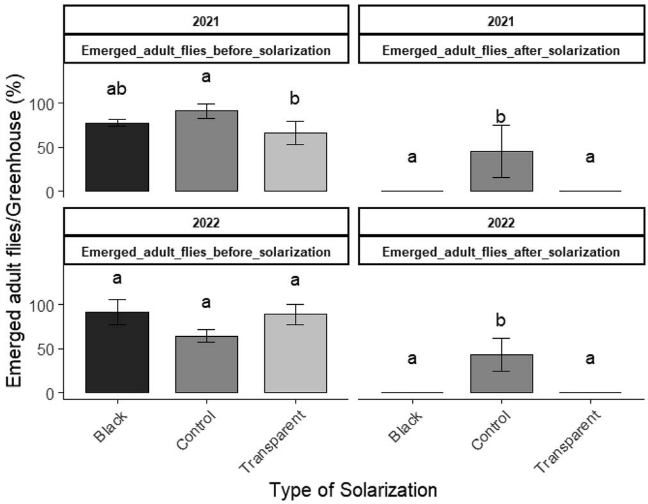

Fig. 2. Mean number of emerged flies per greenhouse for the black, transparent, and control soil solarization treatments at two times, before and after solarization, during 2021 and 2022.

significantly lower compared with the control (unsolarized) soil ($F = 97.86$, df $= 2$, $P < 0.001$). A similar trend was observed in 2022, with fly captures remaining statistically significant ($F = 90.28$, df $= 2$, $P < 0.001$). In 2021, the lowest mean number of flies was recorded in greenhouses covered with black film (3.78 ± 1.07), followed by greenhouses covered with transparent polyethylene films (5.56 ± 0.196). This pattern persisted in 2022, with black film again yielding the lowest mean fly count (3.45 ± 1.35) compared with transparent film (5.33 ± 0.879). Conversely, the unsolarized soil consistently showed the highest fly counts in both years, with means of 19.7 ± 2.40 flies in 2021 and 26.6 ± 3.72 flies in 2022 (Fig. 3).

Fruit infestation. Number of infested fruits. A significant reduction in the number of infested fruits per greenhouse was observed after soil solarization using black or transparent plastic films compared with the control (unsolarized) greenhouses in both 2021 ($F = 16.42$, df $= 2$, $P = 0.0036$) and 2022 ($F = 30.7$, df $= 2$, $P = 0.0007$). In 2021, greenhouses with soil covered with black film recorded the lowest mean number of infested fruits (20.7 ± 5.69), followed by those covered with transparent films (12.7 ± 2.52). This trend was consistent in 2022, with black film treatment yielding 20.3 ± 3.51 infested fruits, whereas transparent films recorded 16.7 ± 4.51 infested fruits (Fig.4).

Infestation rate. The control soil consistently exhibited the highest infestation rates, with 34 ± 5 infested fruits in 2021 and 40.7 ± 4.04 infested fruits in 2022. Similarly, a significant difference in the infestation rate, measured by the number of emerged flies per kilogram of fruit, was observed across greenhouses treated with black or transparent films compared with the control in 2021 ($F = 21.39$, df $= 2$, $P = 0.00186$) and 2022 ($F = 55.91$, df $= 2$, $P = 0.000132$). The lowest average infestation rate was recorded in greenhouses covered with black film, with 75.3 ± 3.07

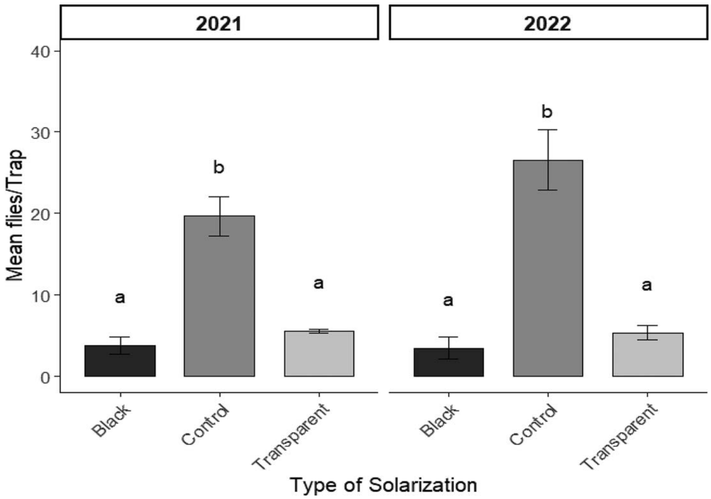

Fig. 3. Mean number of captured flies/trap per greenhouse for the black, transparent, and control soil solarization treatments at two times, before and after solarization, during 2021 and 2022.

flies/kg in 2021 and 73.9 ± 0.57 flies/kg in 2022, compared with greenhouses with transparent film, which showed rates of 63.5 ± 2.17 flies/kg in 2021 and 58.1 ± 3.24 flies/kg in 2022. The unsolarized soils exhibited the highest infestation rates, with 101 ± 11.8 flies/kg in 2021 and 102 ± 8.34 flies/kg in 2022 (Fig.4).

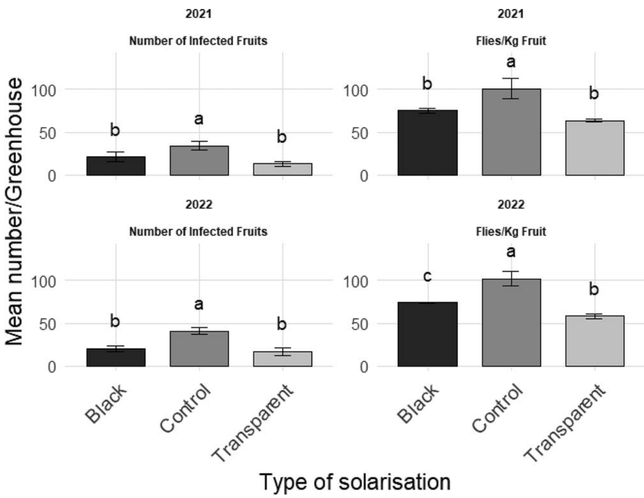

Fig. 4. Mean number of infected fruits and mean number of emerged flies/kg fruit (or infestation rate) per greenhouse for the black, transparent, and control soil solarization treatments after solarization during 2021 and 2022.

Discussion

This study showed the effectiveness of solarization by irrigation with geothermal water at a temperature of 60–70°C using black or transparent polyethylene film to increase soil temperatures during July and August, which significantly reduced *Dacus* pupae in the soil, leading to a reduction in the index and infestation rates during the growing season. Similarly, several studies have demonstrated the effectiveness of this alternative method to chemical control in mitigating various phytosanitary problems. Chellemi et al. (1997) showed that solarization was effective in controlling soilborne pests and pathogens in arid climates. In addition, Katan (1987) and DeVay (1995) reported that increasing soil temperatures to lethal levels affects the life cycles of various pests, including insect pupae, weed seeds, and pathogens. Solarization killed several pathogens, including the bacteria *Pseudomonas solanacearum* (Smith) Smith, *Streptomyces scabies* (Thaxton) Lambert & Loria; the fungi *Fusarium oxysporum* (Schlecht), *Rhizoctonia solani* Kühn, *Phytophthora cinnamomi* Rands; and the nematodes *Criconemella*, *Meloidogyne*, and *Pratylenchus penetrans* (Cobb) Filipjev & Schuurmans-Stekhoven (Bhardwaj et al. 2023, Jagtap et al. 2022, Rokunuzzaman et al. 2016). Solarization can reduce nematode populations by 37–100% because of the increased humidity and toxic volatile compounds generated during the process (Mullaimaran et al. 2022, Sofi et al. 2014).

Therefore, irrigation with water at temperatures between 60 and 70°C could increase the effectiveness of solarization in geothermal greenhouses by reducing the numbers of *Dacus* spp. pupae and thus numbers of emerging fruit fly adults. In addition, solarization was applied during the hottest months, July and August, raising soil temperatures above 50°C, an effect amplified by using black or transparent polyethylene film. The black film proved to be more efficient than transparent film in reaching relatively higher temperatures, confirming previous work showing increased thermal absorption capacity of black plastic film, which increases soil temperature by around 11°C more than transparent film (Mullaimaran et al. 2022). However, other studies show that, in some contexts, transparent films may be more effective in controlling weeds or fungal pathogens (Abo-Dakika 2006, Bawazir and Aidaros 2005). Thus, the increase in soil temperature could be the key factor in reducing the numbers of *Dacus* pupae during solarization. Studies have been conducted on the effect of temperature on the viability of Diptera pupae. *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae) pupae die in 10–25 min at 46°C, in 5–10 min at 48°C, and in 40–60 min at 43°C (Xie et al. 2008), whereas exposure to 40°C for 3 h caused 81% mortality of *Bradysia odoriphaga* (Diptera: Sciaridae) pupae (Shi et al. 2018).

In the example of *D. frontalis*, temperature levels influence the development of each life stage, from egg to adult emergence. An increase in temperature from 25°C to 30°C results in a significant reduction in pupal survival, from 65.65% $\pm$ 4.77% at 25°C to 48.48% $\pm$ 5.23% at 30°C (Hafsi et al. 2024). This shows that increasing temperature leads to a decrease in *Dacus* pupal survival. In our study, in addition to the increase in soil temperature above 50°C, soil saturation by irrigation water could also be influenced by the effect of water stagnation. In addition, greenhouse farmers in Tunisia have successfully adopted soil solarization to control pests such as *Tuta* *absoluta* Meyrick (Lepidoptera: Gelechiidae) by targeting pupae present in the soil (Abbes et al. 2012, Mansour et al. 2019).

In our experiment, the presence of deformed flies with incomplete emergence could confirm that solarization was reaching temperature levels that affect the life cycle of *Dacus* spp. During the Armenian cucumber growing season, solarization demonstrated significant efficacy in reducing the number of adult *Dacus* spp. adults trapped. This reduction was attributed to the decreased emergence of pupae. Furthermore, the fruit infestation index and infestation rates, measured 15 d after fruit set, were lower. However, no significant difference was observed between the greenhouses subjected to solarization, whether covered with black or transparent plastic film. In contrast, a significant difference was observed compared with the untreated control greenhouses.

The reduction in infestation can be attributed to a decrease in the number of *Dacus* spp. pupae, which results in fewer adult flies captured in the traps and, consequently, a lower level of fruit infestation. Despite this reduction, the number of adults in traps and the level of fruit infestation remained relatively high. This may be explained by the emergence of adults from outside the farm (Huat 2019), likely from adjacent farms where solarization was not practiced.

In conclusion, this study demonstrated the effectiveness of solarization as a sustainable pest management method in arid climates, particularly with the use of black polyethylene films targeting *Dacus* pupae in production soils. However, it is important to complement this approach with other methods, such as plant extracts (Zamani et al. 2024) or entomopathogenic fungi (Elghadi and Port 2019), to enhance the management of these two pests. The integration of complementary strategies would help overcome the limitations of solarization, such as external pest sources and environmental concerns.

References Cited

Abbes, K., A. Harbi and B. Chermiti. 2012. The tomato leafminer *Tuta absoluta* (Meyrick) in Tunisia: Current status and management strategies. Eur. Mediterr. Plant Prot. Organ. Bull. 42(2): 226–233.

Abo-Dakika, M.F. 2006. Soil solarization as an environmental friend method for controlling soil-borne fungi infesting tomato plants. J. Plant. Prod. 31(1): 241–247.

Abu-Gharbieh, W., H. Saleh and H. Abu-Blan. 1991. Use of black plastic for soil solarization and post-plant mulching, Pp. 229–237. *In* DeVay, J.E., J.J. Stapleton, and C.L. Elmore (eds.), Soil Solarization. Plant Production and Protection Paper 109. FAO, Rome.

Al-Mtarfi, T.I.T. and N.S. AlShammary. 2023. Evaluation of sticky traps and baits in control of melon fly, *Dacus frontalis* Becker on melon. Inst. Phys. Conf. Ser. Earth Environ. Sci. 1214: 012040. doi:10.1088/1755-1315/1214/1/012040.

Bawazir, A. and A. Aidaros. 2005. Effect of soil solarization on weeds in sesame crop in Delta Tuban, Lahej Governorate, Yemen. Arab. J. Plant Prot. 23: 31–36.

Bhardwaj, S., M. Gupta, S. Gupta and D.K. Mehta. 2023. Soil solarization: An eco-friendly management technique of damping-off of tomato. Int. J. Bio-Resour. Stress Manag. 14(4): 506–511.

Candido, V., T. d'Addabbo, M. Basile, D. Castronuovo and V. Miccolis. 2008. Greenhouse soil solarization: Effect on weeds, nematodes and yield of tomato and melon. Agron. Sustain. Dev. 28: 221–230.

Chellemi, D., S.M. Olson, D. Mitchell, I. Secker and R. McSorley. 1997. Adaptation of soil solarization to the integrated management of soilborne pests of tomato under humid conditions. J. Phytol. 87(3): 250–258.

Cherif, A., Y. Ghalleb and K. Grissa-Lebdi. 2023. Efficacy of food attractants and attract-and-kill system to control *Dacus ciliatus* (Loew) (Tephritidae: Diptera): New recorded pest in Northern Tunisia. J. Entomol. Res. Soc. 25(2): 267–274.

Christenson, L. and R.H. Foote. 1960. Biology of fruit flies. Annu. Rev. Entomol. 5(1): 171–192.

DeVay, J.E. 1995. Solarization; an environment-friendly technology for pest management. Arab J. Plant Prot. 13(2): 97–102.

DeVay, J.E. and J. Katan. 1991. Mechanisms of pathogen control in solarized soils, Pp. 87–102. *In* Katan, J. and J.E. DeVay (eds.), Soil Solarization. CRC Press, Boca Raton, FL.

Dubois, T., S.K. Onsongo, E.R. Omuse, J.A. Odhiambo, K.S. Akutse and S.A. Mohamed. 2023. Efficacy of *Metarhizium anisopliae* against the greater pumpkin fly *Dacus bivitattus*. Sustainability 15(17): 13185.

Ekesi, S., P.W. Nderitu and C.L. Chang. 2007. Adaptation to and small-scale rearing of invasive fruit fly *Bactrocera invadens* (Diptera: Tephritidae) on artificial diet. Ann. Entomol. Soc. Am. 100(4): 562–567.

Elghadi, E. and G. Port. 2019. Use of entomopathogenic fungi for the biological control of the greater melon fly *Dacus frontalis* in Libya, Pp. 251–265. *In* Perez-Staples, D., F. Diaz-Fleischer, P. Montoya, and M. Vera (eds.), Area-Wide Management of Fruit Fly Pests. CRC Press, Boca Raton, FL.

Elmore, C. 1995. Soil solarization, a non-pesticidal method for controlling diseases, nematodes and weeds. Univ. California Div. Agric. Nat. Resources Publ. 21377. Pp. 1–17.

GIL. 2004. Groupement interprofessionnel des légumes (in French). République Tunisienne Ministère de l'Agriculture et des Ressources Hydrauliques et de la pêche, Tunis, Tunisia.

Gill, H.K. and R. McSorley. 2010. Integrated impact of soil solarization and organic mulching on weeds, insects, nematodes, and plant performance. Proc. Annu. Mtg. Florida State Hort. Soc. 123: 308–311.

Hachicha, M., R. Khaldi and A. Mougou. 2012. Irrigation avec l'eau géothermale salée dans le Sud tunisien. Étude Gest. des Sols 19: 91–103.

Hadded, M. 2013. Evaluation de l'utilisation des eaux géothermiques pour la production des légumes sous abris serre à Nefzaoua (Sudouest tunisien) et impératifs de réhabilitation. Rev. Rég. Arides 32: 3–14.

Hafsi, A., K. Abbes and B. Chermiti. 2024. Life-history strategies of an invasive tephritid species *Dacus frontalis* (Diptera: Tephritidae) under different temperatures. Phytoparasitica 52: 1–16.

Hafsi, A., K. Abbes, A. Harbi, S. Ben Othmen, E. Limem, M. Elimem, M. Ksantini and B. Chermiti. 2015. The pumpkin fly *Dacus frontalis* (Diptera: Tephritidae): A new pest of cucurbits in Tunisia. Eur. Mediterr. Plant Prot. Organ. Bull. 45(2): 209–213.

Harbi, A., S. Djebbi, C. Naccache, K. Abbes, B. Chermiti and M.M. Khemakhem. 2022. Identification and differentiation of the cryptic cucurbit fruit fly species *Dacus frontalis*, *Dacus ciliatus* and *Bactrocera cucurbitae* (Diptera: Tephritidae) using PCR–RFLP for quarantine applications. Int. J. Trop. Insect Sci. 42(2): 2041–2047.

Huat, J. 2019. Actes de séminaire de clôture de la phase 1 des projets du RITA Mayotte (2015–2017). Cen. de Coop. Inter. en rech. agro. pour le develop, Paris. Pp. 1–97.

Jabnoun-Khiareddine, H., B. Mejdoub-Trabelsi, R.A.B. Abdallah, R.S. El-Mohamedy and M. Daami-Remadi. 2020. Efficacy of organic amendments and soil solarization against wilt severity and their effects on pathogenic fungi and tomato production. Int. J. Plant Pathol. 9(2): 93–103.

Jagtap, M.P., Y.A. Shinde and N. Khatri. 2022. An investigation on the effect of soil solarization on soil temperature and soil moisture conservation. Arab. J. Geosci. 15(24): 1778.

Katan, J. 1987. Soil solarization, Pp. 77–105. *In* Chet, I. (ed.), Innovative Approaches to Plant Disease Control. John Wiley and Sons, New York.

Keçe, A.F.Ç., B.Ö. Çatal and M.R. Ulusoy. 2019. A new invasive species in Turkey: *Dacus ciliatus* Loew, 1862 (Diptera: Tephritidae). Turk. J. Entomol. 43(1): 25–30.

Linke, K., M. Saxena, J. Sauerborn and H. Masri. 1991. Effect of soil solarization on the yield of food legumes and on pest control. *In* DeVay, J.E., J.J. Stapleton and C.L. Elmore (eds.), Soil Solarization: Proceedings of the First Conference on Soil Solarization, Amman, Jordan. FAO plant production and protection paper 109: 139–154.

Mahmud, M.M., J.C. Akan, Z. Mohammed and N. Battah. 2015. Assessment of organophosphorus and pyrethroid pesticide residues in watermelon (*Citrulus lanatus*) and soil samples from Gashua, bade local government area Yobe State, Nigeria. J. Environ. Pollut. Hum. Health 3(3): 52–61.

Mansour, R., A. Cherif, S. Attia-Barhoumi, L. Zappalà and K. Grissa-Lebdi. 2019. *Tuta absoluta* in Tunisia: Ten years of invasion and pest management. Phytoparasitica 47: 461–474.

Mohamed, M.B. 2003. Multiple integrated use of geothermal resources in Kebili region, southern Tunisia. International Geothermal Conference, Reykjavík, Sept. 2003. Pp. 14–17.

Mullaimaran, S., K. Haripriya and T. Barathkumar. 2022. Effect of soil solarization and organic amendments on root-knot nematode management in tomato nursery. Int. J. Phytol. Res. 2(4): 34–37.

Nigg, H.N., S.E. Simpson, S. Fraser and R.E. Burns. 2000. Greenhouse comparison of traps and lures for fruit flies. Proc. Annu. Mtg. Florida State Hort. Soc. 113: 141–147.

Rasolofoarivao, H., L.R. Ravaomanarivo and H. Delatte. 2022. Host plant ranges of fruit flies (Diptera: Tephritidae) in Madagascar. Bull. Entomol. Res. Lond. 112(1): 1–12.

Rokunuzzaman, M., A. Hayakawa, S. Yamane, S. Tanaka and K. Ohnishi. 2016. Effect of soil disinfection with chemical and biological methods on bacterial communities. Egypt. J. Basic Appl. Sci. 3(2): 141–148.

Shi, C.H., J.R. Hu, Q.W. Wei, Y.T. Yang, J.X. Cheng, H.I. Han, Q.J. Wu, S.I. Wang, B.Y. Xu and Q. Su. 2018. Control of *Bradysia odoriphaga* (Diptera: Sciaridae) by soil solarization. Crop Prot. 114: 76–82.

Sofi, T., A. Tewari, V. Razdan and V. Koul. 2014. Long term effect of soil solarization on soil properties and cauliflower vigor. Phytoparasitica 42: 1–11.

Sowmiya, L., M. Chandrasekaran and R. Soundararajan. 2021. Evaluation of modified cost effective trap designs to enhance the trapping efficiency of fruit flies in snake gourd ecosystem. Int. J. Curr. Microbiol. App. Sci. 10(03): 990–1005.

Steffens, R. 1983. Ecology and approach to integrated control of *Dacus frontalis* on the Cape Verde Islands, Pp. 632–638. *In* R. Cavalloro (ed.), Fruit Flies of Economic Importance. Proc. CEC/IOBC Intern. Symp., Athens, Greece, November 1982.

Susanto, A., M.G. Faradilla, Y. Sumekar, D.H. Yudistira, W. Murdita, A.D. Permana, L. Djaya and S.N. Subakti Putri. 2022. Effect of various depths of pupation on adult emergence of interspecific hybrid of *Bactrocera carambolae* and *Bactrocera dorsalis*. Sci. Rep. 12(1): 4235.

Tjamos, E.C. 1991. Post-plant application of soil solarization for tree crops. FAO Plant Prod. Prot. 109: 243–252.

Xie, Q., B. Hou and R. Zhang. 2008. Thermal responses of oriental fruit fly (Diptera: Tephritidae) late third instars: Mortality, puparial morphology, and adult emergence. J. Econ. Entomol. 101(3): 736–741.

Zamani, M., A. Sonboli, M. Goldansaz, and M.H. Mirjalili. 2024. *In vitro* micropropagation and conservation of endangered medicinal plant *Nepeta asterotricha* Rech. f.(Lamiaceae): Genetic fidelity, phytochemical and biological assessment. Phys. Mol. Biol. Plants 30(1): 67–80.