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Soil Solarization as an Alternative Weed Control Method for Archaeological Sites in the Mediterranean Region

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Abstract: Weed species commonly colonize archaeological sites in the Mediterranean region, which poses many issues for the sites' function and the state of preservation of the monuments. Soil solarization was investigated as an alternative environmentally friendly weed control strategy following legislative limits on the use of herbicides at archaeological sites in Greece. The aim of the study was to evaluate the effectiveness of solarization applied during: (a) summer (the hottest season, as applied in organic and integrated agriculture) and (b) autumn (a season of low tourist activity in archaeological sites), testing two types of plastic mulching: (a) clear and (b) opaque black, and two types of soil preparation: (a) with tillage (as in the agricultural practice of the method) and (b) without tillage. Visual evaluation of the weed control rate suggested that the application of soil solarization during summer resulted in excellent weed control, 100% the following October to December period and over 90% until February. The application of soil solarization during autumn also provided excellent weed control and treatments with clear plastic and tillage resulted in complete (100%) weed control from October to December, while the following month weed control was over 90%. In late March, dry weight of weed biomass was significantly affected by the solarization treatments and it was significantly reduced by treatments with clear plastic. Thus, soil solarization is a sustainable method that has the potential to be used effectively for weed management in archaeological sites of the Mediterranean region. Even treatments without tillage generated excellent weed control during the winter weed flush period and are recommended to protect unexcavated, fragile artifacts. Also, the results of autumn treatments encourage the application of the method during the season of low tourist activity at archaeological sites.

Keywords: integrated weed management; historical site vegetation management; plastic mulching; soil tillage; solarization periods; sustainable weed control

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1. Introduction

Many civilizations were developed in the Mediterranean basin, which is also home to a vast network of cultural heritage monuments. Numerous monuments are placed in archaeological sites or parks, surrounded by large empty spaces in between them that quickly become colonized by herbaceous plants, especially during the rainy season (November to April) [1,2]. Weeds have the potential to cover monuments, obstruct regular maintenance and restoration, restrict visitor access to the site, degrade the site's aesthetics (give the impression of neglect), and raise the risk of fire during the prolonged hot and dry summers of the Mediterranean region [3–5].

The decision to use weed suppression techniques in archaeological sites should be carefully considered, taking into account specific factors. These factors include the physiology and morphological characteristics of the plant species that cause the damage, helping us understand the mechanism of the particular type of deterioration. Additionally, the duration of the treatment's results and whether periodic application is necessary based on the growth rate of the plants should be considered. Lastly, the effectiveness of the method which depends on the plant species and the growth stage, the risks associated with indiscriminate elimination of biodiversity, and the potential for damage to the monument itself should also be evaluated [6].

The typical Mediterranean climate is characterized by mild winters and prolonged droughts. The herbaceous flora found at archaeological sites in the Mediterranean region is adapted to these conditions and is dominated by plants with a short biological cycle (therophytes) that remain in a quiescent (dormant) stage during the warm summer months [7].

According to Greek national law, priority areas for the application of biological control methods include archaeological sites [8]. This aligns with the European Union's Directive, which emphasizes minimizing herbicide use and prioritizing biological measures [9].

Soil solarization is a non-chemical weed control method used in organic and integrated cropping systems [10]. Its effectiveness is dependent on specific climatic conditions, requiring periods of abundant sunlight and high temperatures [11–14]. The method involves covering the soil with clear plastic sheeting after tillage and irrigation to saturation. The plastic sheet traps solar radiation, leading to increased ground temperature through diffusion, under high-moisture conditions [10,15–18]. The duration of soil mulching is approximately six weeks [12], and Mediterranean regions, such as Greece, are well suited for this method due to their high summer temperatures, which facilitate its efficient application [11,13]. Additionally, the method has been reported to be highly effective against weeds in agricultural fields in Greece [19].

Increased temperature and humidity are the primary factors responsible for the thermal death of seeds during solarization [13,16]. The maximum temperatures reached and the cumulative hours of high temperature are critical factors as seed mortality occurs when their tolerance limits are surpassed. Furthermore, the cumulative number of hours in which temperatures surpass a specific threshold during solarization has a significant impact, even if they are not continuous [20,21].

Proper soil irrigation, ideally reaching saturation point, just before mulching with plastic, is crucial for the success of the method [22]. The plastic sheet acts as a barrier, retaining soil moisture throughout the solarization period, eliminating the need for additional irrigation [23]. The role of high humidity during soil solarization is significant, as seeds are more susceptible to high temperatures when present in a wet substrate compared to a dry one [23,24]. Moreover, irrigation promotes seed germination, which is desirable as seedlings are more vulnerable to high temperatures [21]. Additionally, irrigation stimulates microbial activity and facilitates heat transfer to the soil [13] and composite admixtures may be used to enhance water-holding capacity of soils [25,26]. Preparing the soil through tillage before mulching can improve soil water absorption, create a level application area, and facilitate the proper laying of the plastic sheet [16].

The use of transparent plastic for soil solarization has been described by several researchers [10,11,15,27–29]. However, opaque black plastic has also been tested. It was reported that opaque black plastic significantly reduced the number of weeds, although not as effectively as transparent plastic [29], and that the temperature under the opaque plastic sheet was higher than in bare plots but lower than under transparent plastic [23,30,31]. Other studies have shown that the soil temperature under opaque plastic was lower than in unmulched soil but still achieved weed control [32,33]. Black plastic is generally less effective because it absorbs and deflects some heat instead of trapping it as transparent plastic does [13]. However, in cooler or coastal areas, black plastic can be preferred as weeds do not grow beneath it when the air temperature is too low to support their growth, unlike under transparent plastic. In such cases, the black plastic should be kept in place throughout the hottest season for several weeks [34].

Plastic sheets are available in various thicknesses. Thin plastics (25 μm) provide greater heating but are more susceptible to tearing. Slightly thicker sheets (38–50 μm) are more suitable for windy areas and even thicker plastic (>100 μm) can be used for small treated areas. Typically, plastics intended for large-scale solarization are treated with an ultraviolet (UV) inhibitor to slow down degradation caused by sun exposure [34].

Soil solarization has proved to be effective in controlling various weed species, but the effectiveness of the method varies among species [13,16,17,20,31]. Generally, annual winter species are more susceptible to soil solarization compared to annual summer species [10], as the seeds of winter species germinate at lower temperatures and are sensitive to high soil temperatures. As a result, these seeds are killed without germinating during solarization, or even if the seeds germinate, the seedlings perish. Annual summer species are more difficult to control with solarization, however, numerous studies have demonstrated its effectiveness against summer weeds, when applied for a period of 4–6 weeks [35]. It is possible that the high temperatures during solarization may induce seed dormancy in annual summer weeds [21]. Perennial species, on the other hand, are more resistant to soil solarization [10,36], as their underground organs, such as rhizomes, tubers, etc., develop at depths greater than the effective control depth of soil solarization (5–10 cm) and remain protected [13]. Additionally, most perennial species can germinate even from partially damaged underground organs [23].

Archaeological sites represent delicate landscapes with unique preservation requirements, necessitating the implementation of effective weed control strategies. In Greece, the prevailing approach to weed management in these sites has primarily relied on labor-intensive and costly methods such as mowing [37]. However, the suitability and transferability of agricultural practices for weed suppression in archaeological sites have remained relatively unexplored. Given the limitations and expenses associated with current weed control methods applied in these sites, there is a clear need for further research to investigate alternative approaches that are both effective and sustainable. By examining the potential transferability of soil solarization to archaeological sites, this study aims to contribute to the development of more efficient, cost-effective, and environmentally friendly weed control methods that align with the preservation goals of these historically significant landscapes. The findings of this research will provide valuable insights and guidance for the management and conservation of archaeological sites, addressing a critical knowledge gap in the field of weed control in these unique and culturally significant environments.

When applying soil solarization in archaeological sites, careful consideration is necessary to preserve the integrity and cultural significance of the site. The sites may contain unexcavated, valuable, and fragile artifacts and tillage is often not suitable. It is crucial to adhere to proper archaeological protocols and regulations to ensure the preservation and study of the remains as cultural resources. Moreover, during summer, archaeological sites typically experience a higher number of visitors compared to other seasons, with well-known sites sometimes seeing hundreds or even thousands of visitors per day.

This study brings forth a novel approach by investigating the effectiveness of soil solarization without the use of tillage, specifically during the autumn season, which aligns with the period of low tourist activity at archaeological sites. By focusing on these conditions, the study aims to provide valuable insights into the feasibility and effectiveness of soil solarization as an environmentally friendly weed control strategy for archaeological sites, offering a novel perspective on managing weed growth during periods of low visitor activity.

Considering the importance of minimizing soil disturbance and implementing weed suppression methods during periods of lower visitor traffic in archaeological sites, it would be valuable to study the effectiveness of soil solarization without tillage during the autumn season. Therefore, the objective of the study was to assess the effects of two types of plastic mulching (clear and black opaque) and two types of soil preparation (with tillage or without tillage), applied during two solarization periods (summer and autumn), on weed control in Greece.

2. Materials and Methods

2.1. Site Preparation and Experimental Set-Up

The study was conducted at the experimental field of the Agricultural University of Athens, Athens, Greece (37°58′ N and 23°42′ E, 30 m a.s.l.). In consideration of the preservation requirements of archaeological sites, it was not permitted to apply tillage within these sensitive areas. Therefore, to ensure the relevance and transferability of our research findings to the preservation of archaeological sites, we selected a non-cultivated area on the university campus for the experimental study, where annual herbaceous weeds grew abundantly. This approach aimed to mimic the conditions and constraints encountered within archaeological sites, where soil disturbance needs to be minimized to protect unexcavated artifacts and delicate structures.

The plot arrangement followed a split-plot design, with the type of soil mulching being the main plot (two types of plastic and unmulched plot serving as the control). The type of soil preparation was considered as the subplot (with tillage, without tillage). The plot size was 2 × 2 m, and each treatment was replicated 3 times (a total of 18 plots). The soil solarization treatments were applied during two periods: (i) 10 July to 21 August 2014 (summer solarization) and (ii) 19 August to 30 September 2014 (autumn solarization).

Two types of plastic sheets were used: (i) clear (transparent) plastic (Thermosoil, PE, Lugano, Switzerland, 50 µm thickness, Eurofilm Mantzaris SA, Korinthia, Greece) and (ii) opaque black plastic (Black Ground Cover, MDPE-LLDPE, 40 µm thickness, Eurofilm Mantzaris SA, Zevgolatio, Greece).

Soil tillage was applied to half of the plots at a depth of 10 cm before mulching. Then, irrigation was applied at soil saturation to all plots and the clear or opaque plastic sheets were laid accordingly. The edges of the sheets were buried around the perimeter of each plot, creating grooves to secure the plastic sheets in place and prevent gas exchange with the environment, as well as to retain moisture.

Thus, in each period of solarization, the following treatments were applied: (a) clear plastic with tillage, (b) clear plastic without tillage, (c) opaque plastic with tillage, (d) opaque plastic without tillage, (e) unmulched soil with tillage, (f) unmulched soil without tillage.

2.2. Measurements

Temperature probes (PT100, UTECO S.A., Piraeus, Greece) were inserted 5 cm below the soil surface and readings were obtained every 60 min for 4 weeks throughout each application period. Specifically, for the summer solarization period readings were taken from 24 July to 20 August 2014 and for the autumn solarization period readings were taken from 20 August to 19 September 2014. During the same periods, the air temperature at a height of 1 m above ground was recorded every 10 min using a HOBO U23 Pro v2 data logger (Onset Computer Corporation, Bourne, MA, USA).

Following the solarization periods, the overall weed control (control ratings) in each plot was visually evaluated, based on a scale of 0 (plot completely covered by weeds) to 100 (complete weed elimination). Control ratings were obtained every two weeks during the following winter weed flush period, from 6 October 2014 to 23 March 2015. Additionally, weed species were recorded on two dates: 18 November 2014 and 9 February 2015. In the Mediterranean climate, the primary growing season for vegetation typically spans from November to March. In practice, if weeds are controlled until the end of March, they will not pose a significant threat at archaeological sites throughout the dry, hot summer and autumn months due to insufficient soil moisture, which prevents the emergence and growth of new weed flushes, especially of annual species [37].

On the last day of the study, 23 March 2015, aboveground biomass was collected from a 50 × 50 cm area in the center of each plot, and dry weight was determined. The biomass samples were taken to the laboratory, placed in paper bags, and dried for 4 days at 70 °C in an oven (ED 400, BINDER GmbH, Tuttlingen, Germany). After completing the drying process, the samples were removed from the oven and their dry weight was determined.

2.3. Statistical Analysis

To assess the efficiency of the two solarization periods (summer and autumn), data were analyzed using JMP® ver. 8 statistical software (SAS Institute Inc., Cary, NC, USA), with the combination of soil mulching and soil preparation treatments as the main plot and time (sample dates) as the subplot for each treatment period. Furthermore, data were analyzed using the repeated measures model for each solarization period, with the type of soil mulching being the main plot, soil preparation the subplot, and time (sampling dates) the sub-subplot. The analysis of data collected during the autumn period showed significant interactions between soil mulching and soil preparation factors and therefore data for this period were analyzed using the repeated measures model, with the combined treatment of soil mulching and soil preparation as the main plot and time (sampling dates) as the subplot. Treatment means were separated using Fisher's protected least significant difference (LSD), at a 0.05 probability level ($p < 0.05$).

To compare the effect of the different solarization periods on the dry weight of aboveground biomass, collected from the plots, data were converted to g m^{-2} and analyzed using the one-way analysis of variance employing JMP® ver. 8 (SAS Institute Inc.). For each solarization period, the effect of mulching type and soil preparation on aboveground biomass dry weight was evaluated using a two-way analysis of variance. In both analyses, treatment means were separated using Fisher's protected least significant difference (LSD) at a 0.05 probability level ($p < 0.05$).

3. Results

3.1. Air and Soil Temperature

The air temperature varied between the two treatment periods and was higher during summer than in the autumn solarization period (Figure 1). Over a 4-week period, the cumulative time during which the air temperature exceeded 30 °C was 254 h for summer treatments and 122 h for autumn treatments.

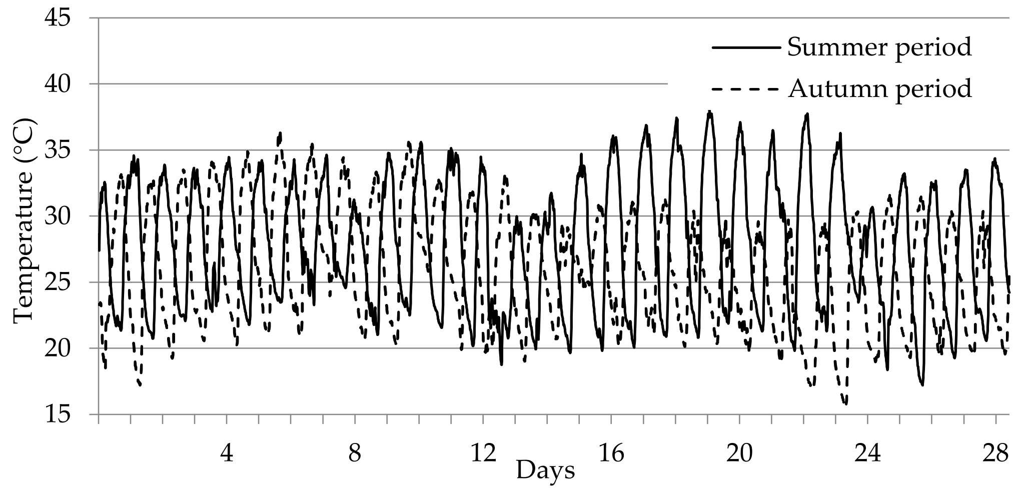

Figure 1. Air temperature during a four-week period, i.e., 24 July to 20 August 2014 for the summer solarization period and 20 August to 19 September 2014 for the autumn solarization period.

The temperature of the soil varied depending on the type of mulching used and the treatment period. The highest soil temperatures were recorded during the summer application period, where the maximum daily temperatures ranged from 35 °C to 48 °C in plots covered with clear plastic, 33 °C to 45 °C in uncovered plots, and 34 °C to 40 °C in plots that were covered with opaque black plastic (Figure 2). During the summer solarization period, the cumulative number of hours when the soil temperature exceeded 40 °C was 238 h under the clear plastic, followed by 122 h in control plots and 27 h under the opaque plastic.

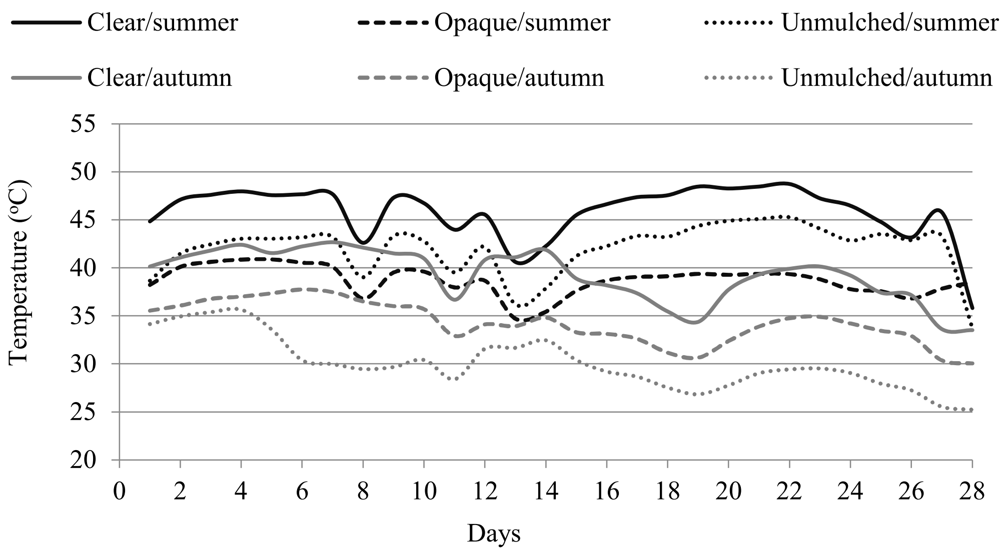

Figure 2. Maximum daily soil temperature during a four-week period, i.e., 24 July to 20 August 2014 for the summer solarization period and 20 August to 19 September 2014 for the autumn solarization period.

Similarly, the highest temperatures were recorded under clear plastic throughout the autumn solarization period, with maximum daily temperatures ranging from 33 °C to 42 °C, compared to 25 °C to 35 °C in uncovered plots and 30 °C to 37 °C under opaque plastic (Figure 2). During the autumn treatments, soil temperatures exceeded 40 °C for 54 h under clear plastic but not under opaque plastic or in unmulched plots.

3.2. Overall Weed Control

The soil solarization treatments with both clear and opaque plastic significantly reduced the weed growth compared to control plots. The solarization period had a significant effect on the level of weed control (Table 1). The summer solarization period achieved a higher level of control, with over 90% weed control during October 2014 and over 60% for approximately two more months during the winter weed flush period (Figure 3). The level of control in the plots solarized during summer gradually declined after January 2015 to about 35% and dropped below 20% by the end of March 2015. The autumn treatments resulted in a reduced degree of control, with around 70% control during October and 35–50% control for the next two months during the winter weed flush period. After January, the level of control gradually declined and dropped below 20% after February.

Table 1. The effect of solarization period (summer, autumn), following the repeated measures model with the solarization period as the main plot and time (sampling dates) as the subplot, on the level of weed control (%). Means derive from pooled data over the whole study period (October 2014 to March 2015).

Source of Variation	df	F-Value
Treatment period (A)	1	72.38 ***
Time (B)	14	51.68 ***
A × B	14	0.67 NS
Treatment period		Level of weed control (%)
Summer		56.62 a †
Autumn		37.91 b
LSD		4.64

*** Significant at $p < 0.001$; NS non-significant at $p < 0.05$; † values are the mean of 18 replicates. Means in columns followed by different letters are significantly different at $p < 0.05$ using Fisher's least significant difference (LSD).

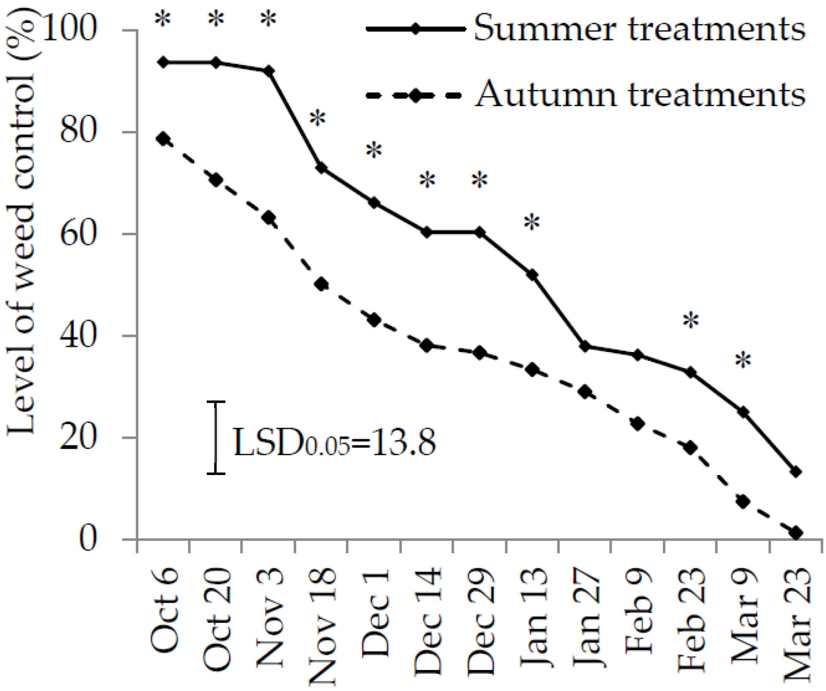

Figure 3. Level of weed control as affected by solarization period, during weed flush period (October 2014 to March 2015). Values are the mean of 18 replicates. Asterisks (*) indicate significant differences between treatment means on a single sampling date according to Fisher's least significant difference (LSD) at $p < 0.05$ following the repeated measures model.

The two-way data analysis of treatments in the summer solarization period showed no significant interactions between the main factors of the study, namely the type of soil mulching (clear or opaque plastic) and type of soil preparation (tillage or no tillage) (Table 2). The effectiveness of summer solarization was significantly affected mainly by the type of plastic mulching and secondarily by the type of soil preparation. The highest level of weed control was achieved with the clear plastic, resulting in excellent weed control, 100% from October to December and over 90% until February, which gradually declined during March to 40% (Figures 4 and 5). The opaque plastic resulted in lower levels of control, starting with almost complete weed control (>90%) in October, which decreased to about 60% in the following two months and fell below 20% in subsequent months. The control plots started to sprout during October and by mid-November the level of control was significantly lower, dropping to about 30% and decreasing to 0% in January (Figure 4).

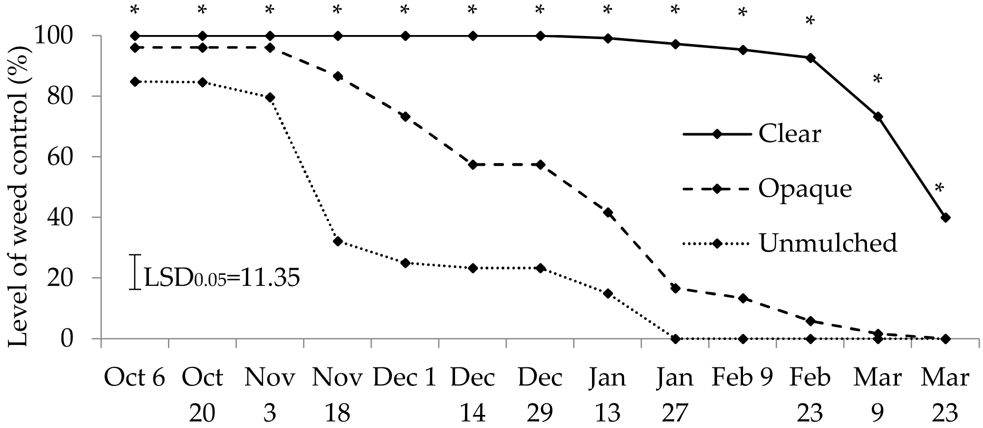

Figure 4. Level of weed control of plots treated during summer, as affected by the type of soil mulching, during the winter weed flush period (October 2014 to March 2015). Values are the mean

of six replicates. Asterisks (*) indicate significant differences between treatment means on a single sampling date according to Fisher's least significant difference (LSD) at $p < 0.05$ following the repeated measures model.

Table 2. The effect of the type of soil mulching and soil preparation, when plots were treated during summer, following the repeated measures model, with the type of soil mulching as a main plot, soil preparation as the subplot, and time (sampling dates) as sub-subplot, on the level of weed control (%).

Source of Variation	df	F-Value
Type of soil mulching (A)	2	518.64 ***
Type of soil preparation (B)	1	31.12 **
Time (C)	12	155.57 ***
A × B	2	3.94 ^{NS}
A × C	24	26.44 ***
B × C	12	5.42 ***
A × B × C	24	6.33 ***
Type of soil mulching		Level of weed control (%)
Clear		92.13 a †
Opaque		49.42 b
Unmulched		28.31 c
LSD		5.61
Type of soil preparation		
With tillage		63.97 a
Without tillage		49.26 b
LSD		6.45

, * Significant at $p < 0.01$ and $p < 0.001$, respectively; ^{NS} non-significant at $p < 0.05$; † values are the mean of six replicates for the type of soil mulching and nine replicates for the type of soil preparation. Means in columns followed by the same letter are not significantly different at $p < 0.05$ using Fisher's least significant difference (LSD).

Soil tillage improved the level of control and over 70% weed control was observed from October to December, whereas in the plots without tillage the level of control had dropped to about 40%, over the same period (Figures 5 and 6).

The two-way data analysis of the autumn solarization showed significant interactions between the main factors of the study, i.e., type of soil mulching, type of soil preparation (Table 3). Treatments with clear plastic and tillage resulted in excellent weed control, achieving complete (100%) weed control from October to December 2014, while the following month weed control was over 90% (Figures 7 and 8). After January 2015, the level of control in plots treated with clear plastic and tillage gradually decreased, dropping below 20% in March 2015. Similar results were obtained in plots treated with clear plastic, without tillage. The treatment with opaque plastic and tillage, during autumn, resulted in 100% weed control in October and over 80% by mid-November, after which the plots started to sprout and the level of control dropped below 20% by December 2014. Similar results were obtained with the use of opaque plastic without tillage (Figure 7). The control plots, with or without tillage, started to sprout early and the level of control had dropped below 20% by the end of October 2014.

Figure 5. Images of plots that have undergone solar solarization during summer, as affected by the type of soil mulching and soil preparation, during the winter weed flush period.

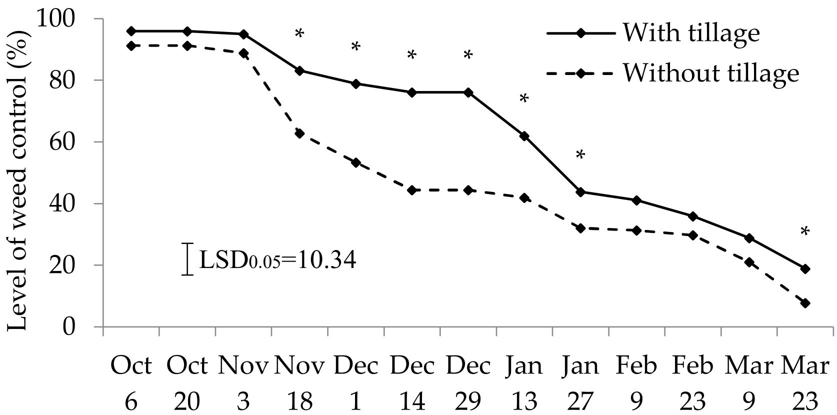

Figure 6. Level of weed control of plots treated during summer, as affected by the type of soil preparation, during the winter weed flush period (October 2014 to March 2015). Values are the mean of nine replicates. Asterisks (*) indicate significant differences between treatment means on a single sampling date according to Fisher's least significant difference (LSD) at $p < 0.05$ following the repeated measures model.

Table 3. The effect of treatments (combined effect of type of soil mulching and soil preparation), when plots were treated during autumn, following the repeated measures model, with treatments as a main plot and time (sampling dates) as the subplot, on the level of weed control (%).

Source of Variation	df	F-Value
Treatments (A)	5	509.02 ***
Time (B)	12	462.1 ***
A × B	60	71.74 ***
Treatments		Level of weed control (%)
Clear plastic with tillage		80.83 a †
Clear plastic without tillage		77.11 a
Opaque plastic with tillage		37.38 b
Opaque plastic without tillage		24.74 c
Unmulched soil with tillage		4.79 d
Unmulched soil without tillage		2.56 d
LSD		4.79

*** Significant at $p < 0.001$; † values are the mean of three replicates. Means in columns followed by the same letter are not significantly different at $p < 0.05$ using Fisher's least significant difference (LSD).

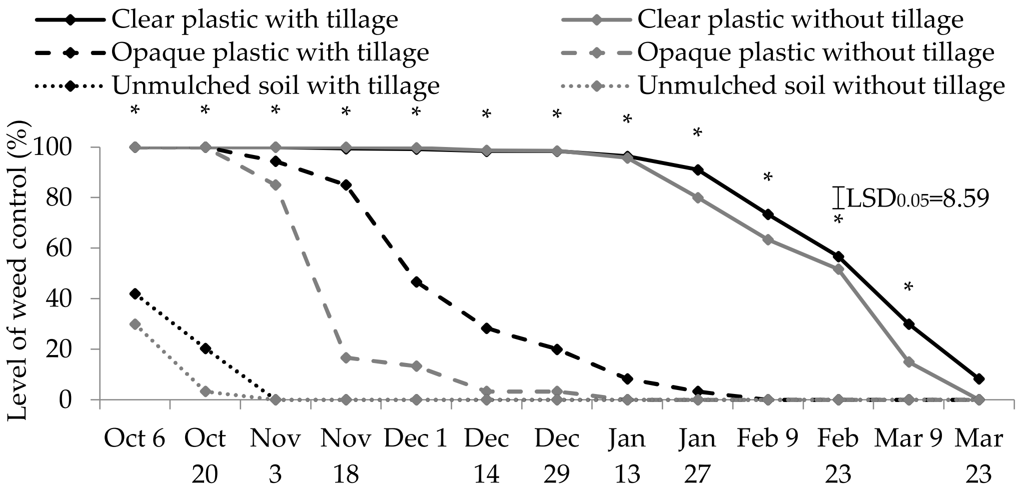

Figure 7. Level of weed control (%), of plots treated during autumn, as affected by the treatments (combined effect of type of soil mulching and soil preparation), during the winter weed flush period. Values are the mean of three replicates. Asterisks (*) indicate significant differences between treatment. means on a single sampling date according to Fisher's least significant difference (LSD) at $p < 0.05$ following the repeated measures model.

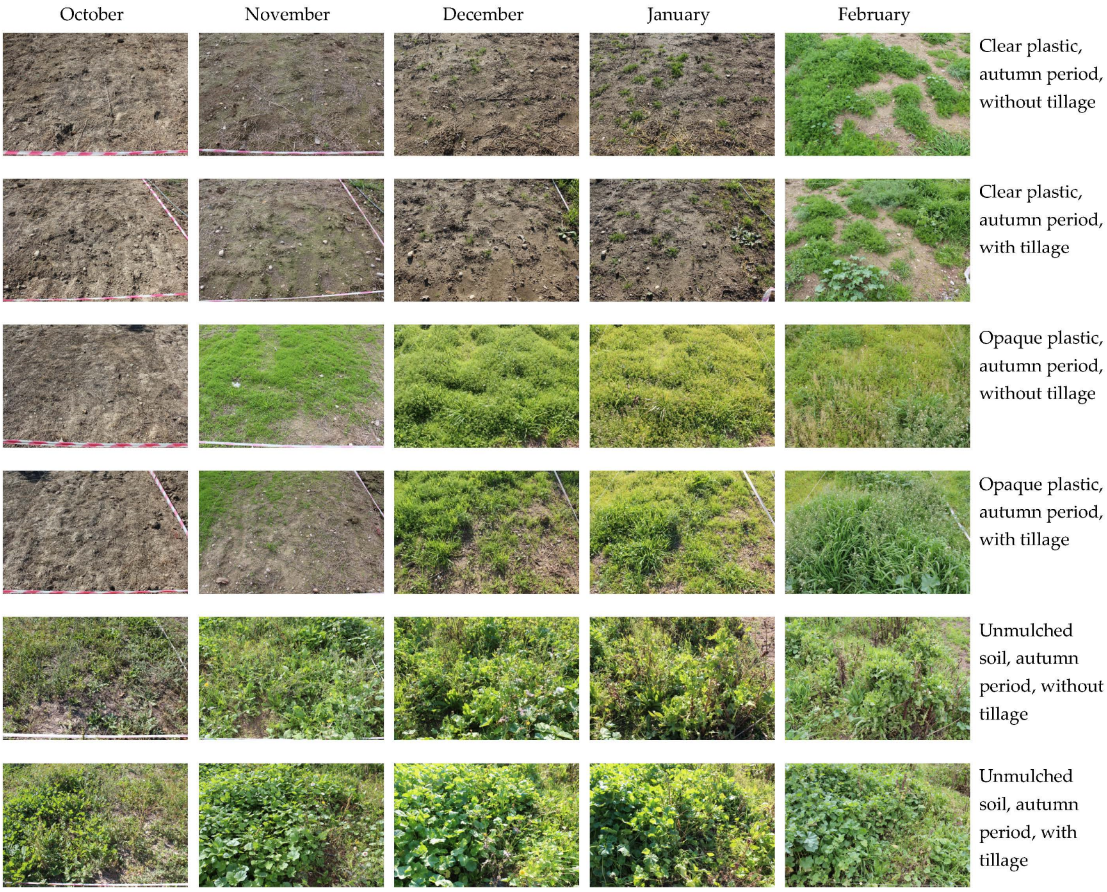

Figure 8. Images of plots that have undergone solar solarization during autumn, as affected by the type of soil mulching and soil preparation, during the winter weed flush period.

3.3. Weed Species

In two recordings made in November 2014 and February 2015 of weed species appearing in plots after solarization treatments, a total of 25 different species were found exhibiting high heterogeneity, making it difficult to draw any conclusions about the species-specific effectiveness of the method. The species recorded in the plots after solarization treatments were: *Amaranthus retroflexus*, *Avena sterilis*, *Bromus hordeaceous*, *Capsella bursa pastoris*, *Chenopodium album*, *Convolvulus arvensis*, *Cyperus rotundus*, *Erodium malacoides*, *Fumaria arabica*, *Gallium aparine*, *Heliotropium europaeum*, *Hordeum murinum*, *Lactuca seriola*, *Lamium amplexicaule*, *Malva sylvestris*, *Matricaria recutita*, *Medicago* sp., *Oryzopsis miliaceae*, *Poa annua*, *Senecio vulgaris*, *Setaria viridis*, *Sinapis arvensis*, *Sonchus oleraceus*, *Tribulus terrestris*, and *Veronica persica*.

3.4. Dry Weight Biomass

The application period of solarization significantly affected the dry weight of weed biomass collected from the plots at the end of March 2015. Summer solarization resulted in significantly less biomass (379.21 g m^{-2}) compared to autumn solarization (570.54 g m^{-2}, Table 4).

In summer solarization, the best results were obtained with the clear plastic, which yielded only 74.42 g m^{-2} of biomass, significantly less compared to the opaque plastic (567.19 g m^{-2}) and the uncovered plots (496.04 g m^{-2}, Table 5). The tillage factor did not show significant differences in the dry weight of biomass and yielded 372.69 g m^{-2} and 385.74 g m^{-2} of biomass with and without tillage, respectively (Table 5).

Table 4. The effect of the two solarization periods (summer 2014, autumn 2014) on the dry weight of weed biomass (g m^{-2}) collected end of March 2015.

Source of Variation	df	F-Value
Solarization period	1	4.94 *
Solarization period		Dry weight of collected biomass (g m^{-2})
Summer		379.21 b †
Autumn		570.54 a
LSD		174.99

* Significant at $p < 0.05$; † values are the mean of 18 replicates. Means in columns followed by different letters are significantly different at $p < 0.05$ using Fisher's least significant difference (LSD).

Table 5. The effect of the type of soil mulching and soil preparation, in the summer solarization period, on the dry weight of weed biomass (g m^{-2}) collected end of March 2015.

Source of Variation	df	F-Value
Type of soil mulching (A)	2	103.35 ***
Type of soil preparation (B)	1	0.19 ^{NS}
A × B		1.96 ^{NS}
Type of soil mulching		Dry weight of collected biomass (g m^{-2})
Clear		74.42 b †
Opaque		567.19 a
Unmulched		496.04 a
LSD		80.72
Type of soil preparation		
With tillage		372.69 a
Without tillage		385.74 a
LSD		65.91

*** Significant at $p < 0.001$; ^{NS} non-significant at $p < 0.05$; † values are the mean of six replicates for the type of soil mulching and nine replicates for the type of soil preparation. Means in columns followed by the same letter are not significantly different at $p < 0.05$ using Fisher's least significant difference (LSD).

Similar results concerning the main experimental factors were observed in the autumn solarization. Significantly less biomass was collected from plots with clear plastic, 297.92 g m^{-2}, while plots with opaque plastic yielded 559.86 g m^{-2} of biomass and uncovered plots produced the highest biomass of 853.83 g m^{-2} (Table 6). The tillage factor did not show significant differences in biomass with 549.08 g m^{-2} and 591.99 g m^{-2} with and without tillage, respectively (Table 6).

Table 6. The effect of the type of soil mulching and soil preparation, during the autumn 2014 solarization period, on the dry weight of weed biomass (g m^{-2}) collected end of March 2015.

Source of Variation	df	F-Value
Type of soil mulching (A)	2	16.62 ***
Type of soil preparation (B)	1	0.3 ^{NS}
A × B		1.43 ^{NS}
Type of soil mulching		Dry weight of collected biomass (g m^{-2})
Clear		297.92 c †
Opaque		559.86 b
Unmulched		853.83 a
LSD		210.18
Type of soil preparation		
With tillage		549.08 a
Without tillage		591.99 a
LSD		171.61

*** Significant at $p < 0.001$; ^{NS} non-significant at $p < 0.05$; † values are the mean of six replicates for the type of soil mulching and nine replicates for the type of soil preparation. Means in columns followed by the same letter are not significantly different at $p < 0.05$ using Fisher's least significant difference (LSD).

4. Discussion

The results are consistent with those of Vizantinopoulos and Katranis [19] and Horowitz et al. [23] who found that in plots that were covered with clear plastic during summer, four months of sufficient weed control was achieved. The soil solarization treatments significantly reduced the weed growth during the winter weed flush period, suggesting that the method can be effective against many weed species, as indicated by previous reports [10,13,16].

The results are consistent with soil temperature measurements, which indicated that temperatures under the clear plastic rose to levels capable of killing the weed seeds, whereas the opaque plastic mulching failed to raise the soil temperature to critical levels. The highest level of weed control was achieved with clear plastic during the summer solarization period, which also had the highest recorded temperatures for the largest sum of hours (238 h $T \geq 40$ °C). Furthermore, it was observed that, even though temperatures exceeded 40 °C for only 54 h in plots covered with clear plastic during the autumn solarization period, it was still effective in reducing weeds. It has been reported that exposure to temperatures above 40 °C for 50 h in moist soil was enough to kill 90% of winter annual weed seeds [19] and that a minimum of 15 h exposure to 46 °C was necessary to achieve thermal death in weed seeds depending on the species [10]. This finding aligns with previous reports that the cumulative number of hours above a threshold temperature and the maximum temperatures reached during solarization are crucial to the mortality of weed seeds [20,21].

The treatments utilizing transparent plastic demonstrated superior effectiveness in weed control compared to those employing opaque plastic, aligning with corroborating findings from prior studies [29].

Although high temperatures were recorded (122 h $T \geq 40$ °C) in the uncovered plots (controls) during the summer of 2014, weeds grew abundantly in the subsequent winter. This can be attributed to the fact that the seeds in the soil were dry during the high-temperature period. Previous reports have indicated that exposing dry seeds to temperatures of 40–50 °C for 168 h did not significantly reduce seed germination rates. Similarly, exposure to 60 °C for 7 days reduced the germination rates only slightly [24]. On the contrary, exposure of wet seeds to 50 °C for 7 days decreased the germination rates, depending on the species [24]. The extreme conditions created by soil solarization that cause seed death are high temperatures combined with high soil moisture, since the seeds are more sensitive to high temperatures when wet [16,24]. Plastic mulching retains moisture in the plots; thus, no further watering is required during the period of soil solarization [23]. The action mechanism is similar to the thermal method of weed control that involves irrigating with hot water, but it is an economically unsound and impractical method, as it requires very large amounts of energy and water to create the proper conditions [38], which is in contrast to soil solarization, which is a simple method of modifying the soil environmental conditions.

Soil solarization involves tillage before covering the soil with plastic sheeting [16,17,23]. Indeed, in our experiments, the effectiveness of solarization was increased by the tillage treatments, but the results of the treatments without tillage were very encouraging and indicate that solarization can be used without soil preparation. This is crucial in the sensitive environment of archaeological sites, where soil disturbance is avoided to protect unexcavated, fragile artifacts.

Regarding the aesthetic issues raised for the laying of plastic sheets, during the application of soil solarization, it is argued that the method is not permanent, but can be applied periodically, in the context of an integrated weed management program. A major advantage of soil solarization is that when extensive weed control is achieved for the current year, it reduces the number of seeds in the soil that can produce weeds the following year. According to studies, the effectiveness of the current year's weed control is heavily influenced by the effectiveness of the previous year's weed management, whereas decreasing soil seed potential lowers the overall cost of weed control over time [39,40]. Soil solarization can be used to reduce weed populations for a few years, but no more applications should be made until it is deemed necessary again, as solarization has been found to have residual effect [36]. Further, the results of autumn treatments with clear plastic encourage the application of the method during the season of low tourist activity at archaeological sites.

While our study was conducted on an experimental field, the principles and techniques employed in soil solarization can be extrapolated to large surfaces between monuments in archaeological sites. By implementing soil solarization, it is possible to reduce weed growth on these surfaces. By reducing the overall weed population and depleting the soil seed bank, the potential for weeds to colonize monuments and archaeological structures is significantly diminished. As weeds are often the primary source of seeds that can disperse onto monuments, suppressing weed growth in the vicinity can also help minimize their presence on the structures themselves. This reduction in weeds and soil seed bank, facilitated by the soil solarization method, contributes to the preservation and aesthetics of the archaeological site by reducing the need for regular maintenance and restoration, enhancing visitor access, and mitigating the risk of fire.

Future research perspectives could include the repeated application of the soil solarization method and longer-term monitoring of weed suppression. Conducting studies that assess the impact of multiple solarization cycles on weed populations can elucidate the cumulative effects of the method. By evaluating the weed control efficacy and potential changes in soil properties over successive applications, the optimal frequency and duration of soil solarization treatments can be determined. Furthermore, longer-term monitoring of weed suppression following soil solarization is crucial for understanding the durability and persistence of the method's effects [36].

Soil solarization is a non-chemical weed suppression method that can be applied in accordance with legislations stating that in archaeological sites biological control methods should be applied with priority [8,9]. Soil solarization utilizes the Sun's natural energy to heat the soil and the energy input required for the process is relatively low compared to other pest control methods. It does not rely on fossil fuels or external energy sources, making it a relatively energy-efficient technique. It can be implemented without significant alterations to the natural landscape, minimizing potential environmental impacts and preserving the overall ecosystem balance.

We emphasize the responsible use and management of plastic sheets during and after soil solarization, as they can be a serious environmental problem [41]. Collecting plastic sheets after their application is crucial to prevent degradation and the potential release of microplastics into the environment. If plastic sheets are degraded and no longer suitable for reuse, we strongly advocate for their proper disposal and recycling. Considering the environmental implications, it is essential to explore and evaluate sustainable alternatives that minimize the environmental footprint of soil solarization practices. Biodegradable sheets, mulches of sprayable degradable polymers, or starch-based biodegradable films can be a promising avenue for future research [42–45].

5. Conclusions

The months between October and mid-March are the period of the most abundant growth of weeds in archaeological sites of the eastern Mediterranean region. The current study's findings indicate that the soil solarization method can entirely prevent weed emergence for three to four months (October–January), during a period when vegetation is abundant. Thus, soil solarization can be a potential tool for weed management at archaeological sites. Clear plastic mulching, which resulted in the highest soil temperatures, provided the best weed control. The results showed that, even without tillage pretreatment, solarization generated good results and is recommended to reduce labor costs and protect ancient remains that have not been unearthed. Additionally, the results of autumn treatments with clear plastic encourage the application of the method during the season of low tourist activity at archaeological sites. The method can be applied as part of an integrated weed management program to reduce soil seed potential and weaken weed populations.

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