sustainability

MDPI

Article

Sustainable Agrivoltaic Farming: The Role of Mycorrhiza in Promoting Mint Cultivation and High-Quality Essential Oil Production

Bihter Çolak Esetlili [1,*], M. Tolga Esetlili [1], Kaan Emir [2] and Murat Eröz [2]

[1] Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Ege University, Bornova, Izmir 35100, Türkiye; tolga.esetlili@ege.edu.tr

[2] Enerjisa Enerji Üretim A.Ş., Barbaros Mah, Lale Sok., Ataşehir, İstanbul 34746, Türkiye; kaan.emir@enerjisauretim.com (K.E.); murat.eroz@enerjisauretim.com (M.E.)

* Correspondence: bihter.colak@ege.edu.tr

Abstract: Agriphotovoltaic (Agri-PV) systems are a dual-purpose solution for resolving land utilization conflicts through combining agricultural practices and photovoltaic power generation. However, the reduced light intensities and altered microclimatic conditions under PV modules may have negative effects on the productivity of crops. This study investigated whether incorporating arbuscular mycorrhizal fungi (AMF) inoculation into Agri-PV systems could mitigate such limitations for mint cultivation (*Mentha arvensis* and *Mentha* × *piperita*). A field trial was conducted in Bandırma, Türkiye, where both mint species were grown under and between PV panels, with and without AMF. The photosynthetically active radiation (PAR), temperature, fresh biomass, nutrient uptake, and essential oil content were evaluated. PAR was reduced by more than 90% under panels, while air temperatures were 1.0–1.6 °C lower than those in the between-panel areas. AMF inoculation significantly improved the yield and quality. In *Mentha arvensis*, the fresh herb yield increased by 43.4% (from 10,620 to 15,230 kg ha^{-1}), and the essential oil content reached 10.08% under between-panel mycorrhizal conditions. For *Mentha* × *piperita*, the highest menthol concentration (30.38%) was observed exclusively in between-panel plots with AMF. In contrast, the highest oil content (4.50%) was achieved under shaded, mycorrhizal conditions, indicating that both light exposure and microbial interactions shape biochemical responses. This is the first study to demonstrate the synergistic impact of AMF inoculation and agrivoltaic shading on essential oil crops. This paper presents a novel and sustainable model that enhances crop productivity and biochemical quality in solar-integrated agriculture.

Keywords: agrivoltaic; mycorrhiza; *M. piperita*; *M. arvensis*; quality

Academic Editor: Tiziana Amoriello

Received: 23 April 2025

Revised: 9 June 2025

Accepted: 10 June 2025

Published: 16 June 2025

Citation: Çolak Esetlili, B.; Esetlili, M.T.; Emir, K.; Eröz, M. Sustainable Agrivoltaic Farming: The Role of Mycorrhiza in Promoting Mint Cultivation and High-Quality Essential Oil Production. *Sustainability* **2025**, *17*, 5516. https://doi.org/10.3390/su17125516

1. Introduction

Since the Industrial Revolution, increasing greenhouse gas emissions have led to human-induced climate change, posing one of the most significant challenges to modern civilization. Therefore, promoting renewable energy sources in the energy sector and gradually phasing out fossil fuels are essential strategies for mitigating climate change [1]. In recent years, solar energy, as a renewable energy source, has been increasingly integrated into various sectors as an innovative and sustainable approach [2,3]. In this context, photovoltaic (PV) technologies, which have become a cornerstone of climate and energy strategies worldwide, stand out [4,5]. However, this technology requires a substantial amount of land, as 1.5–3.5 hectares of land are needed to generate 1 MW of electricity [6]. Particularly in Mediterranean countries, the unplanned expansion of photovoltaic systems places significant pressure on agricultural production [7]. To address this, agrivoltaic systems, which integrate solar energy generation with agricultural production through mixed-use areas where crops are cultivated under and between PV panel rows, offer key solutions to enhance both environmental sustainability and economic efficiency [5,7]. These systems support sustainable agriculture by enabling energy generation with solar panels that are installed on agricultural lands [8]. However, PV panels can influence the microclimate, the light regime, and water efficiency, and they generate electromagnetic fields that impact soil microorganisms [9,10]. Thus, sustainable management practices aimed at monitoring and enhancing the flora and fauna of the soil in photovoltaic areas could lead to the establishment of ecologically based agrivoltaic systems. Approaches to improve soil health can enhance the success of these systems while minimizing environmental impacts. Despite this potential, research addressing practices to improve soil fertility in agrivoltaic systems remains limited [11,12].

Mycorrhizal fungi, in symbiotic relationships with plants, play a crucial role in enhancing nutrient uptake, reducing water stress, and supporting soil biodiversity in agriculture [13,14]. Numerous studies have demonstrated the effectiveness of arbuscular mycorrhizal fungi (AMF) inoculation to improve the growth of medicinal and aromatic plants for producing essential oils and to increase the yield and content of the main oil components. Positive impacts of AMF inoculation have been reported in several medicinal and aromatic plants, including *Mentha arvensis* L. [15], *Coriandrum sativum* L. [16], *Ocimum basilicum* L. var. *Genovense* [17], *Origanum* sp. [18], *Rosmarinus officinalis* L. and *Ocimum basilicum* L. [19], *Inula ensifolia* L. [20], *Artemisia umbelliformis* Lam. [21], and *Mentha piperita* L. [22,23].

The global market for mint essential oils is exhibiting a significant growth trend, with projections indicating that it will reach USD 14.58 billion by 2025 and expand to USD 23.17 billion by 2029 [24]. This increase is largely driven by high demand from the cosmetics, pharmaceutical, food, and aromatherapy sectors. In contrast, mint oil production in Türkiye remains limited. According to 2020 data, Türkiye's mint oil imports amounted to USD 3.7 million, making it the most imported essential oil in the country [24,25]. This highlights the strategic economic importance of increasing domestic production and developing sustainable production models. Belonging to the Lamiaceae family, with over 60 species, mint (*Mentha* spp.) has long been utilized in food, beverages, chewing gum, and confectionery, as well as in traditional medicine, due to its rich contents of secondary metabolites [26]. Peppermint oil, in particular, is known for its beneficial effects on the digestive, central nervous, and respiratory systems and exhibits anti-inflammatory, antibacterial, antiviral, anticancer, and antioxidant properties [27,28]. Mint oils and menthol hold significant global economic value owing to their widespread use in pharmaceuticals, cosmetics, and the food industry [29,30]. Essential oil of mint contains key compounds such as menthol, menthone, menthyl acetate, menthofuran, and 1,8-cineole, along with non-volatile constituents such as flavonoids, phenolic acids, amino acids, nucleosides, and terpenoids [31]. These components are primarily responsible for the plant's anti-inflammatory and antiviral activities. However, their ratio and concentration are influenced by various factors, including the soil's fertility, environmental conditions, the harvest timing, and species differences [28,32].

Mentha arvensis L. and *Mentha* × *piperita* L. are among the most extensively cultivated mint species due to their high essential oil contents and economically important constituents. *M. arvensis* typically thrives in temperate zones of Europe and parts of Asia, including western and central regions, and its essential oil is characterized by high concentrations of menthol (30–50%) and menthone (15–30%), as well as lesser amounts of menthyl acetate (3–10%) and minor terpenes (1–5%) [33]. *Mentha* × *piperita*, which originated as a natural hybrid of *M. viridis* and *M. aquatica* in Mediterranean ecosystems, produces an essential oil that is rich in menthol (~36%), menthone (~21%), menthyl acetate (~7%), and various secondary metabolites such as eucalyptol (~7%), isomenthone (~5%), neomenthol (~4%), menthofuran (~3%), D-limonene (~2%), β-caryophyllene (~2%), pulegone (~1%), and β-pinene (~1%) [34,35]. The essential oils and secondary metabolites that are obtained from these species comprise numerous bioactive phytochemicals that are used in treating various diseases. The growth and oil composition of mint have been improved using various organic fertilizers, biofertilizers, and plant growth regulators. Agrivoltaic systems are thought to have positive effects on mint cultivation through their microclimatic influence and optimized water use [10]. By partially blocking direct sunlight on mint plants, solar panels can prevent overheating and are expected to support healthier plant growth [36].

Although agrivoltaic systems have been studied extensively, their integration with beneficial soil microorganisms, particularly arbuscular mycorrhizal fungi (AMF), has received limited attention [37,38]. Addressing this research gap, the present study investigates the combined effects of agrivoltaic shading and AMF inoculation on the agronomic performance of *Mentha piperita* L. and *Mentha arvensis* L. Specifically, it examines how mycorrhizal and non-mycorrhizal conditions influence the yield, essential oil content, and oil composition of these mint species when cultivated beneath photovoltaic panels. By highlighting the synergies between energy-efficient land use and soil microbiome management, the findings provide valuable insights for sustainable agriculture and offer practical implications for the future development of agrivoltaic systems.

2. Materials and Methods

2.1. Experimental Location and Design

The experiment was carried out at EnerjiSA's photovoltaic test site, situated in Bandırma, North Aegean, Türkiye (see Figure 1). The photovoltaic panels that were used during the study had a length of 1.2 m, a width of 0.6 m, a thickness of 6.8 mm, and an angle of inclination of 25 degrees. The entire system had a combined electricity generation capacity of 2354.7 kilowatts peak (kWp).

Figure 1. Location of the agrivoltaic experimental site in Bandırma, Türkiye, where the field trials were conducted under photovoltaic panels installed by EnerjiSA. (The red circle marks the experimental area).

Bandırma is classified under the Köppen system as having a Mediterranean climate (Csa), which supports mint cultivation due to its hot summers and moist, temperate winters [39]. The climatic profile of Bandırma includes an average annual temperature of 14 °C and an average precipitation level of 685 mm per year (Table 1).

Table 1. Monthly variations in rainfall and temperature in the mint cultivation area [39].

Parameter	Jananury	February	March	April	May	June	July	August	September	October	November	December
Avg Temp (°C)	5.8	6.7	9.2	13.0	18	22.7	25.2	25.3	21.6	16.5	12.0	7.7
Min Temp (°C)	2.7	3.1	5	8.4	13.3	18.1	21	21.6	17.9	13.4	8.8	4.7
Max Temp (°C)	9.1	10.4	13.6	17.6	22.6	27	29.5	29.5	25.6	20	15.5	10.8
Precip. (mm)	81	77	73	53	44	39	22	19	44	69	72	102
Humidity (%)	79	78	73	71	68	64	62	64	67	75	77	80.0
Rainy Days	9.0	8	8	6	5	5	3	3	5	6	7	10
Avg. Sun Hours	4.6	5.4	7.1	8.8	10.2	11.5	11.6	10.4	8.8	6.3	5.4	4.7

In the experiment, two different mint varieties (*Mentha* × *piperita* and *Mentha arvensis*) were grown under mycorrhizal and non-mycorrhizal conditions, between and under panels in agrovoltaic fields (Figure 2). The experiment was established during the June 2024 production season using a randomized plot design with three replications, as detailed below:

PM0: Non-mycorrhizal, between the panels;
PM1: Mycorrhizal, between the panels;
PAM0: Non-mycorrhizal, under the panels;
PAM1: Mycorrhizal, under the panels.

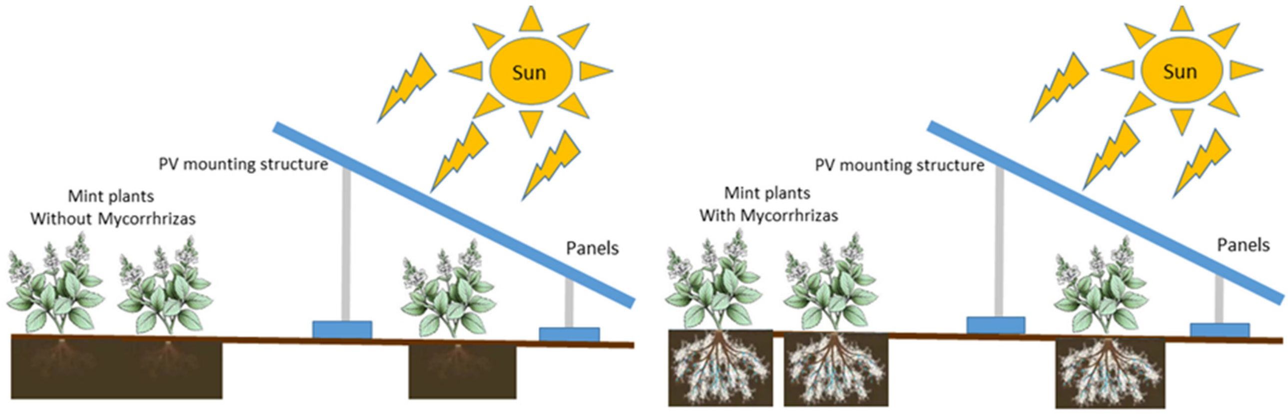

Figure 2. Diagram of the experiment.

Each experimental plot covered an area of 100 m^2. Mint seedlings, sourced from a certified supplier, were planted under and between the photovoltaic (PV) panels at a density of 6 plants per square meter, using a spacing of 50 × 25 cm. Approximately 3 to 4 months prior to planting, 10 tons per hectare of well-decomposed farmyard manure were incorporated into the soil beneath and between the panels. This amendment aimed to improve the soil's fertility and create optimal growing conditions in the shaded areas, thereby enhancing crop productivity. During planting and again 10 days later, a commercial vesicular–arbuscular mycorrhizal (VAM) inoculum (Cosme Biotech Group, India), consisting of a consortium of three Glomus species, was applied directly to the root zone. The formulation contained 100,000 infective propagules per kilogram and comprised three distinct, highly adaptable VAM species belonging to the genus Glomus. The development of the plants was monitored for an average of 90 days, and harvesting was carried out after the onset of flowering. After harvesting, the fresh weights of the plants were determined.

2.2. Collection of Microclimate Data

The microclimate conditions were monitored using data loggers (HOBOconnect, Monitoring App., Sydney, Australia), which enabled the uninterrupted measurement of the atmospheric and terrestrial conditions. An ATMOS 14 (METER, München, Germany) sensor was used to measure the air temperature and relative humidity, while the solar radiation and soil moisture content were measured using PYR and TEROS 11 sensors (METER, München, Germany), respectively. To ensure accurate measurements, the ATMOS 14 and PYR sensors were housed 60 cm above ground level, while the TEROS 11 sensors were installed 20 cm below ground level.

Along with the above-mentioned ATMOS 14 and PYR sensors, PAR measurements were taken using an Onset Computer Corporation (Bourne, MA, USA)-developed S-LIA-M003 Photosynthetic Light (PAR) Smart Sensor (ONSET, Bourne, MA, USA). This sensor has been especially designed to measure 400–700 nm wavelengths of light. The sensors were positioned under (UP) and between (BP) photovoltaic (PV) modules for observation of the spatial variation in light distribution caused by shading. The sensors were connected to a common H21-USB Data Logger, which recorded PAR readings systematically on an hourly basis over the plants' growth periods. The data logger recorded fine-scale temporal data, which was then collated and averaged for further examination.

2.3. Soil Characterization

Soil fertility analyses were conducted using samples collected from three different locations within both the under-panel (UP) and between-panel (BP) areas of the agrivoltaic field. The results were averaged and are presented in Table 2.

Table 2. Physical and chemical properties of the Bandırma experimental soil.

Soil			Between Panels 0–30 cm	Under Panels 0–30 cm
	O.M.%		1.91	2.18
	Total N%		0.10	0.13
Available	P	mg/kg	18.9	19.4
	K		493	377
	Na		203	240
	Mg		1054	995
	Fe		11.51	12.57
	Zn		0.55	0.69
	Mn		21.15	23.30
	Cu		1.83	1.80
	pH		7.17	7.09
	Texture		Sandy clay loam	Sandy clay loam
	EC dS/m		0.87	0.94
	$CaCO_3$%		2.47	2.05

The soil texture was analyzed using the hydrometer method developed by Bouyoucos [40]. The pH and electrical conductivity (EC) of the soil were measured in a 1:1 (w/v) suspension of soil and distilled water, employing a pH meter and a glass electrode EC meter, respectively. The calcium carbonate ($CaCO_3$) content was quantified using the Scheibler calcimeter method, while organic matter was determined via the Walkley–Black wet oxidation procedure [41]. Total nitrogen (N) was assessed using the Kjeldahl digestion method, and plant-available phosphorus (P) was measured according to the Olsen extraction technique [41,42]. Exchangeable bases, including potassium (K), calcium (Ca), and magnesium (Mg), were extracted with 1 N ammonium acetate (NH_4OAc, pH 7.0) and subsequently analyzed using atomic absorption spectrophotometry (Varian spectra AA220FS spectrometer; Varian Inc., Mulgrave, Victoria, Australia). The micronutrient concentrations of iron (Fe), copper (Cu), zinc (Zn), and manganese (Mn) were determined using 1 N DTPA (pH 8.2) as the extractant, allowing assessment of their bioavailable fractions in the soil [40].

The soil fertility analyses revealed noticeable variations between the soils that were located beneath the photovoltaic panels (under-panel) and those between the panel rows (between-panel). Prior to the establishment of the experiment, well-composted farmyard manure was applied uniformly across the entire field at a rate of 10 tons per hectare. However, due to the reduced exposure to direct rainfall beneath the panels, it is likely that nutrient leaching in these shaded zones was minimal. As a result, the concentrations of organic matter, total nitrogen (N), available phosphorus (P), sodium (Na), and certain micronutrients were found to be higher in the under-panel soils than in the between-panel areas. This suggests that the microclimatic conditions created by the panel shading may have contributed to enhanced nutrient retention and reduced losses, thereby influencing the spatial distribution of soil fertility parameters within the agrivoltaic system.

2.4. Plant Analysis

The mint plants, which were harvested from each plot at the end of September, were washed with distilled water in the laboratory and then dried at 65–70 °C for 48 h. The dried samples were ground and prepared for plant nutrient element analyses. The total nitrogen (N) content of plants was determined using a modified Kjeldahl method. The phosphorus (P) content was measured colorimetrically using the vanadomolybdophosphoric yellow color method with dry ash extract [43]. Elemental analysis was performed using two techniques; flame photometry was employed for the quantification of K, Ca, and Na, while the Mg, Fe, Zn, Mn, and Cu levels were determined using atomic absorption spectrophotometry (Varian spectra AA220FS spectrometer; Varian Inc., Mulgrave, Victoria, Australia) [40,43].

Essential oil extraction was carried out using the hydrodistillation method. Plant material was collected just before full flowering. Specifically, the upper one-third of each plant (containing flowers, buds, and young leaves) was harvested. The harvested material was then shade-dried at room temperature, following a previously described protocol [44]. Distillation was conducted using a Clevenger-type apparatus in accordance with a previously outlined protocol [40].

The obtained essential oil samples were stored in dark glass bottles at 4 °C and protected from light until analysis. Qualitative and quantitative analyses of essential oils were conducted using gas chromatography (GC) and gas chromatography–mass spectrometry (GC-MS) techniques. The chemical composition of the essential oils was identified using a GC-MS system (Hewlett-Packard—HP 6890 GC System, Agilent Technologies Inc., Santa Clara, CA, USA), coupled with a selective mass detector (HP 5973) and equipped with an HP-5 capillary column (60 m × 0.25 mm internal diameter, 0.25 μm film thickness). The GC-MS analysis was performed using an electron ionization (EI) source at 70 eV. Helium was used as the carrier gas at a constant flow rate of 1.0 mL min^{-1}. The quantitative analysis of the essential oils was performed by comparing the retention times of sample compounds with those of commercial standards of major constituents. Additionally, the arithmetic indices calculated from compound retention times in an alkane series using an FID detector were matched with the reported retention index data [45–47].

2.5. Statistical Analyses

The effects of fertilizer treatments for each experimental year were assessed using analysis of variance (ANOVA), followed by multiple comparisons of means via the least significant difference (LSD) test. All statistical evaluations were conducted using the JMP Pro 16 software package.

3. Results

3.1. Photosynthetically Active Radiation (PAR)

The average PAR values, measured at midday, revealed significant differences between the two areas. As expected, the areas under the panels (UP) consistently showed lower PAR values, ranging approximately between 60.6 and 272.8 µmol m^{-2} s^{-1} and with an average value of 124 µmol m^{-2} s^{-1}. The between-panel (BP) areas showed notably higher PAR values, ranging between 986 and 2429 µmol m^{-2} s^{-1} and averaging around 2085 µmol m^{-2} s^{-1}. This substantial reduction in PAR under the panels aligns with findings from previous studies on agrivoltaic systems, indicating significant impacts of shading on the availability of solar radiation for plants beneath PV panels (Figures 3 and 4) [48–50].

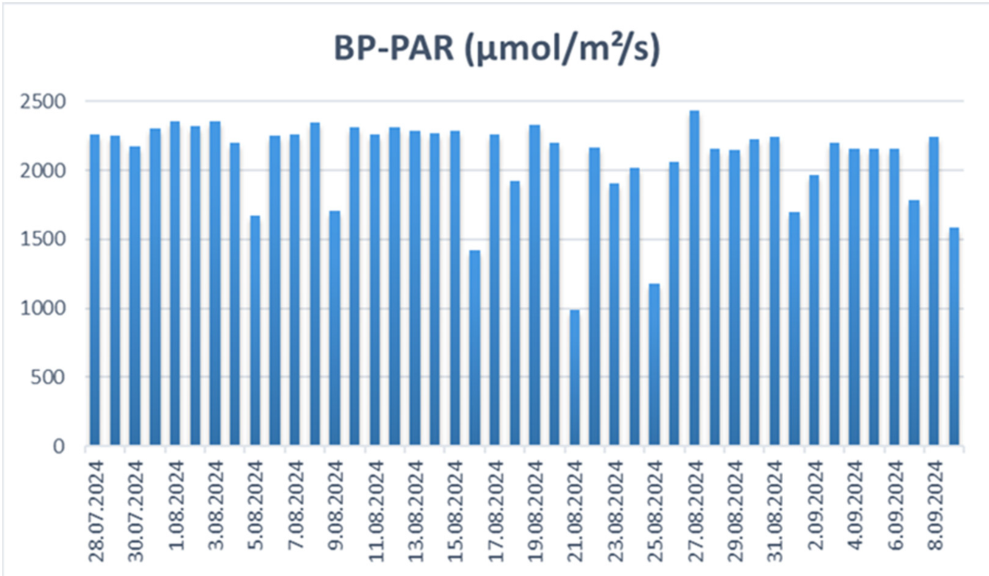

Figure 3. The mean solar radiation throughout the crop cycle, measured in the between-panel (BP) areas across different dates.

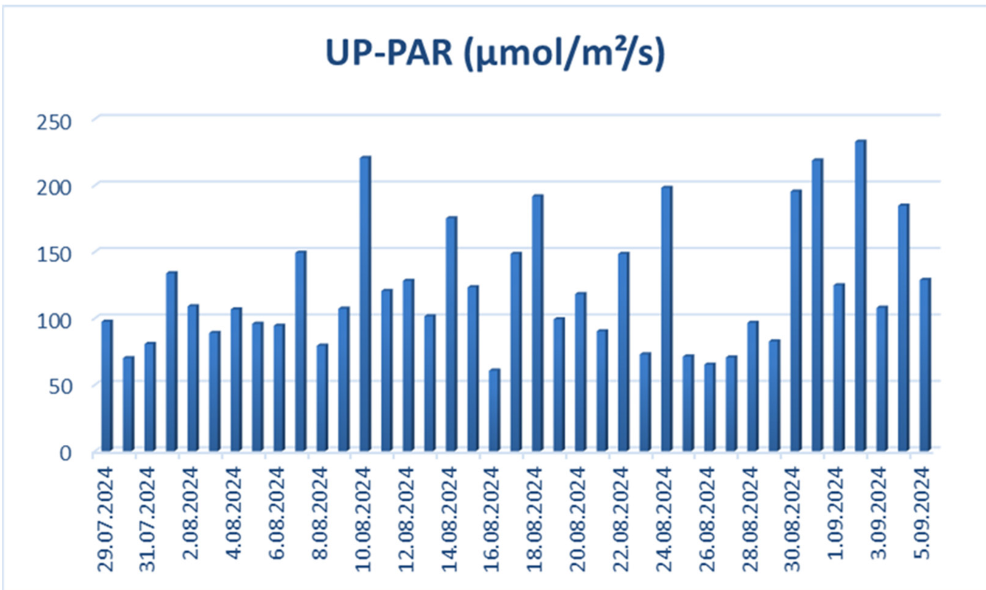

Figure 4. Throughout the growing period, the solar radiation beneath the panels (UP) showed variation in average values across different dates.

3.2. Temperature Analysis

The air temperature measurements, taken concurrently with PAR measurements at approximately 13:00 h, showed notable differences. The UP areas were always cooler compared with the BP areas. On average, the temperatures of the areas under panels were approximately 1.0–1.6 °C lower than those measured between panels. This temperature reduction was in accordance with findings reported by previous studies, highlighting that shading from photovoltaic panels reduces air temperatures, thereby potentially moderating plant canopy temperatures and reducing plant water stress, ultimately enhancing the water use efficiency (Figure 5).

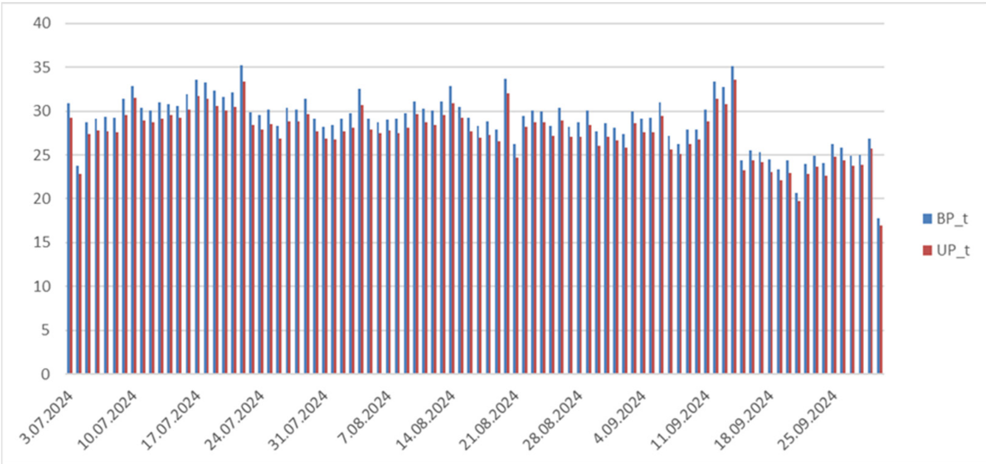

Figure 5. Average air temperatures under (UP) and between panels (BP).

3.3. *Mentha arvensis* vs. *Mentha* × *piperita* Yield and Macro- and Micronutrient Elements

It has been observed that mycorrhiza applications significantly influence the yield of mint that is cultivated in agrivoltaic systems, particularly in between-panel areas (Tables 3 and 4). For *Mentha arvensis*, the highest yield (15,230 kg ha^{-1}) was obtained from between-panel areas treated with mycorrhiza (PM1), whereas the lowest yield (6250 kg ha^{-1}) occurred in under-panel areas without mycorrhiza application (PAM0) (Table 3). In the case of *Mentha piperita*, the highest yield (18,190 kg ha^{-1}) was recorded in between-panel areas with mycorrhiza application (PM1), but this yield was not statistically different from that of the between-panel areas with no mycorrhizal treatment. Conversely, under-panel conditions clearly demonstrated the positive impact of mycorrhiza, yielding up to 13,490 kg ha^{-1} (Table 4). Accordingly, it can be concluded that mint yield may vary significantly under agrivoltaic conditions depending on the cultivar; however, biomass production can substantially increase with mycorrhiza treatments in both between- and under-panel areas. Specifically, the shading provided by photovoltaic panels appears particularly beneficial for yield and quality parameters in *Mentha piperita*.

Table 3. Fresh yield and macronutrient contents of *Mentha arvensis*.

	Fresh Herb Yield kg/ha	**N %**	**P %**	**K %**	**Na %**	**Ca %**	**Mg %**
PM0	10,620 ab	2.80 b	0.20 c	2.20 c	0.19 b	2.07 b	0.60
PM1	15,230 a	2.81 b	0.26 bc	2.31 bc	0.29 ab	2.10 b	0.61
PAM0	6250 b	3.35 a	0.28 b	2.44 ab	0.38 a	2.14 b	0.60
PAM1	9580 ab	3.40 a	0.40 a	2.60 a	0.19 b	2.70 a	0.60
SD	125	0.029	0.015	0.041	0.003	0.093	0.051
p	**	**	**	**	**	*	ns

* $p < 0.05$; ** $p < 0.01$; ns: non-significance. Lowercase letters denote comparisons between treatments and data sharing the same letter are not significantly different from each other, n = 3.

Table 4. Fresh yield and macronutrient contents of *Mentha piperita*.

	Fresh Herb Yield kg/ha	N %	P %	K %	Na %	Ca %	Mg %
PM0	15,720 a	2.63 c	0.30 ab	2.07 b	0.06 b	1.51 c	0.90
PM1	18,190 a	2.85 bc	0.35 a	2.32 b	0.04 b	1.93 ab	0.87
PAM0	9730 b	3.24 ab	0.27 b	2.61 a	0.09 a	1.64 bc	0.89
PAM1	13,490 ab	3.35 a	0.26 b	2.67 a	0.09 a	2.10 a	0.89
SD	100	0.086	0.012	0.058	0.002	0.06	0.032
p	**	**	**	*	*	**	ns

* $p < 0.05$; ** $p < 0.01$; ns: non-significance. Lowercase letters denote comparisons between treatments and data sharing the same letter are not significantly different from each other, n = 3.

Mycorrhizal inoculation under agrivoltaic conditions significantly affected the macronutrient uptake in both mint species (Tables 3 and 4). For *Mentha arvensis*, the nitrogen (N) contents were generally higher in under-panel areas, although the effect of mycorrhizal application on the plants' N content was limited. The highest N content (3.40%) was recorded under mycorrhizal conditions under panels (PAM1). Furthermore, the phosphorus (P) uptake in *Mentha arvensis* was notably enhanced by mycorrhizal inoculation; for instance, in under-panel conditions, the P content increased up to 0.40% compared with the 0.28% of the no-mycorrhiza (PAM0) treatment. Similarly, plants under between-panel conditions showed a moderate increase in P contents, reaching 0.26% with mycorrhizal application (PM1) and 0.20% without mycorrhiza (PM0). The potassium (K) content exhibited a similar trend, with the highest level (2.60%) being obtained under PAM1 conditions and the lowest (2.20%) under PM0 conditions. Interestingly, the highest calcium (Ca) and sodium (Na) contents were observed under PAM0 conditions in *Mentha arvensis*. The magnesium (Mg) contents did not show statistically significant differences between treatments.

Comparable trends were observed for *Mentha* × *piperita*, highlighting that mycorrhizal treatments in under-panel conditions notably improved the N, K, Na, and Ca uptake. The highest N (3.35%), K (2.67%), and Ca (2.10%) contents were recorded in the under-panel, mycorrhiza-treated *Mentha* × *piperita*. The phosphorus content peaked (0.35%) under between-panel conditions with mycorrhizal application. Although the Mg content was not statistically affected by the treatments, variability in Mg uptake was evident between mint varieties, with *Mentha* × *piperita* demonstrating higher Mg levels than *Mentha arvensis*. These findings suggest that the mycorrhizal inoculation significantly enhanced macronutrient uptake, thus promoting plant growth under agrivoltaic conditions.

Regarding the micronutrient contents of mint varieties grown under agrivoltaic conditions, our results confirmed a positive influence of mycorrhizal inoculation on micronutrient uptake (Tables 5 and 6).

Table 5. Micronutrient contents of *Mentha arvensis* (mg/kg).

	Fe	Mn	Zn	Cu
PM0	262 b	29 b	40 c	32
PM1	274 b	39 b	48 b	39
PAM0	474 a	39 b	48 b	31
PAM1	482 a	86 a	60 a	37
SD	12.57	3.55	0.68	1.80
p	*	*	**	ns

* $p < 0.05$; ** $p < 0.01$; ns: non-significance. Lowercase letters denote comparisons between treatments and data sharing the same letter are not significantly different from each other, n = 3.

Table 6. Micronutrient contents of *Mentha piperita* (mg/kg).

	Fe	Mn	Zn	Cu
PM0	276 b	37 b	32	33 b
PM1	287 b	64 ab	35	33 b
PAM0	350 a	56 ab	37	30 b
PAM1	365 a	79 a	39	56 a
SD	6.85	6.45	1.71	1.76
p	*	**	ns	*

* $p < 0.05$; ** $p < 0.01$; ns: non-significance. Lowercase letters denote comparisons between treatments and data sharing the same letter are not significantly different from each other, n = 3.

The iron (Fe) content in *Mentha arvensis* was notably influenced by the growing conditions and mycorrhizal inoculation. For example, the Fe concentration in the mint plants that were grown between the panels was found to be 262 mg/kg (PM0), while it was 482 mg/kg when grown under mycorrhiza-inoculated under-panel conditions (PAM1). Similarly, in *Mentha* × *piperita*, the highest Fe content (365 mg/kg) was recorded in PAM1, while the lowest (276 mg/kg) occurred under PM0 conditions. Additionally, the manganese (Mn) and zinc (Zn) contents in *Mentha arvensis* reached their maximum levels in mycorrhizal under-panel conditions. For *Mentha* × *piperita*, the Mn and copper (Cu) concentrations were highest under PAM1 conditions, whereas the Zn content did not differ significantly between treatments.

These findings highlight the substantial benefits of mycorrhizal inoculation for mint cultivation under photovoltaic systems. Mycorrhiza applications enhanced the nutrient availability in the root zone, positively affecting the health and biomass production of plans. Particularly, the shading that was provided by the panels may have reduced nutrient leaching, increased the soil's organic matter retention, and improved its water-holding capacity, thereby enhancing the mint yield and macronutrient uptake.

3.4. Essential Oil Yield and Components

The shading and microclimatic conditions provided by photovoltaic (PV) panels in agrivoltaic systems significantly influence the yield and composition of mint essential oils. Furthermore, when combined with mycorrhizal inoculation under and between PV panels, the soil's fertility can be sustainably managed, enhancing the effectiveness of agrivoltaic systems in terms of the yield of mint essential oil and its constituents (Tables 7 and 8). The yield and composition of essential oils vary notably between mint species. *Mentha arvensis* primarily contains menthol, menthone, limonene, isomenthone, neomenthol, and germacrene-D, while *Mentha* × *piperita* oil composition prominently features menthol, menthone, menthofuran, isomenthone, 1,8-cineole, and menthol acetate.

Table 7. Composition of essential oil yield and *Mentha arvensis* components.

	EO %	Menthol %	Menthone %	Limonene %	İsomenthone %	Neomenthol %	Germacren-D %
PM0	6.67 b	66.02	9.83	3.42 a	4.40	2.16	1.42 b
PM1	10.08 a	65.91	11.50	3.07 b	4.69	2.26	1.68 a
PAM0	7.33 ab	67.91	10.71	3.02 b	4.90	2.32	1.20 c
PAM1	7.92 ab	68.56	10.20	1.38 c	4.69	2.42	1.49 ab
SD	0.70	1.14	0.71	0.067	0.19	0.065	0.042
p	**	ns	ns	**	ns	ns	**

** $p < 0.01$; ns: non-significance. Lowercase letters denote comparisons between treatments and data sharing the same letter are not significantly different from each other, n = 3.

Table 8. Composition of essential oil yields and *Mentha piperita* components.

	EO %	Menthol %	Menthone %	Menthofurane %	İsomenthone %	1,8 Cineol %	Menthol Acetate %
PM0	3.23 b	25.66 b	32.37 b	15.76 ab	3.56	5.35 b	1.70 bc
PM1	3.67 b	30.38 a	20.35 d	12.33 b	3.51	5.44 b	3.25 a
PAM0	3.33 b	27.46 ab	27.07 c	16.34 a	3.86	6.60 a	2.03 b
PAM1	4.50 a	18.79 c	41.90 a	15.46 ab	3.44	6.52 a	0.89 c
SD	0.34	0.76	0.74	0.72	0.20	0.19	0.21
p	*	**	**	*	ns	*	**

* $p < 0.05$; ** $p < 0.01$; ns: non-significance. Lowercase letters denote comparisons between treatments and data sharing the same letter are not significantly different from each other, n = 3.

Comparing the oil yields of both mint species, our results showed that *Mentha arvensis* generally had higher yields, with the highest (10.08%) being in the treatment group grown in between-panel plots and receiving mycorrhizal inoculation (PM1). In contrast, the highest essential oil yield from *Mentha* × *piperita* (4.50%) was obtained in the under-panel treatment with mycorrhizal application (PAM1). While mycorrhizal treatments increased the oil yields from *Mentha arvensis,* especially under between-panel conditions, in *Mentha* × *piperita*, the combination of shading from photovoltaic panels and mycorrhizal inoculation enhanced oil production.

L-menthol, the primary compound giving mint its characteristic cooling sensation, which is widely used in the cosmetic, pharmaceutical, and food industries, was significantly higher in *Mentha arvensis* than in *Mentha* × *piperita*. The highest L-menthol content (68.56%) in *Mentha arvensis* was recorded in the under-panel treatment with mycorrhiza (PAM1); however, the statistical differences among treatments were not significant. For *Mentha* × *piperita*, the highest L-menthol level (30.38%) was recorded in the between-panel mycorrhizal treatment plants (PM1), whereas the lowest (18.79%) was observed in plants grown under the panels and with mycorrhizal application. L-menthol can be biosynthesized from menthone through enzymatic processes, which are influenced by environmental factors such as the water stress, temperature, and soil fertility, as well as genetic factors inherent to the plant. No significant effects of treatments were observed for the menthone content in *Mentha arvensis*. For *Mentha* × *piperita,* the highest menthone concentration (41.90%) was recorded in under-panel mycorrhizal (PAM1) conditions, and the lowest (20.35%) was recorded in the between-panel mycorrhizal treatments (PM1).

The limonene content in *Mentha arvensis* reached its peak (3.42%) under between-panel conditions without mycorrhiza (PM0), while the germacrene-D content was highest (1.68%) under between-panel mycorrhizal conditions. The effects of treatments on the isomenthone and isomenthol contents were statistically insignificant. For *Mentha* × *piperita*, menthofuran reached the highest level (16.34%) under the under-panel conditions without mycorrhiza (PAM0). The 1,8-cineole content in *Mentha* × *piperita* was higher in the under-panel areas than in between-panel areas, whereas the menthol acetate content peaked (3.25%) under between-panel mycorrhizal treatment (PM1). These results demonstrate that agrivoltaic conditions can variably influence essential oil synthesis in different mint varieties by affecting the secondary metabolism associated with plant stress responses. Additionally, mycorrhizal treatments appear to play an important role in essential oil biosynthesis under agrivoltaic conditions.

4. Discussion

In this study, the effects of arbuscular mycorrhizal fungi (AMF) inoculation on the growth, nutrient content, yield, and essential oil composition of *Mentha arvensis* and

Mentha × *piperita* were studied under agrivoltaic conditions in Bandırma, Turkey. Our results indicated that mycorrhiza treatments significantly enhanced nutrient uptake and essential oil production in both mint varieties, demonstrating substantial contributions toward sustainable agricultural production. In addition, the photosynthetically active radiation (PAR) and temperature variations under the fixed photovoltaic (PV) panels were measured. The microclimatic conditions of the areas under (UP) and between (BP) the panels were examined.

Partial shading, recognized as a sustainable agricultural practice, has been shown to positively influence the yield and quality of mint, particularly when combined with mycorrhizal inoculation. The fresh herb yield of *Mentha arvensis* has been reported to range from 9460 to 37,500 kg per hectare, with essential oil contents between 1.68% and 2.72%, of which menthol constitutes 75.9% to 79.3% [51]. For *Mentha piperita*, the fresh yields range from 14,200 to 31,500 kg/ha in Germany and 6700 to 13,500 kg/ha in Türkiye, with essential oil contents reported to be between 2.40% and 2.85% [52]. In the present study, the effects of mycorrhizal application under photovoltaic panel shading and in between-panel areas were evident for both mint species. For *Mentha arvensis*, the fresh herb yield ranged from 6250 to 15,230 kg/ha, with essential oil contents between 6.67% and 10.08%. In *Mentha* × *piperita*, yields ranged from 9730 to 18,190 kg/ha, and the essential oil contents varied between 3.23% and 4.50%. These findings underscore the synergistic benefits of combining agrivoltaic shading with AMF applications to enhance both productivity and secondary metabolite accumulation in mint cultivation.

Agrivoltaic systems have emerged as a novel and holistic strategy that integrates photovoltaic energy production with agricultural activities on the same land unit. The shading effect provided by photovoltaic (PV) panels helps regulate microclimatic conditions by increasing the soil surface temperatures during colder seasons and reducing excessive heat stress during summer. This thermal buffering contributes to soil moisture conservation and enhances the nutrient uptake efficiency by minimizing evapotranspiration losses [53]. In this study, the soil samples collected from beneath the panels were observed to contain higher levels of certain nutrients than samples taken from the between-panel areas. This finding suggests that PV panels may help preserve the nutrient content in soil by shielding it from adverse environmental factors such as rainfall, wind erosion, and extreme heat. Additionally, the partial shading provided by the panels can enhance the near-surface water availability by promoting nocturnal dew formation and may also lead to temperature differentials between the areas beneath and between the panels. Beyond these agronomic benefits, crop cultivation under PV arrays can facilitate passive cooling of the panels, thereby improving the photovoltaic conversion efficiency. When properly designed and managed, agrivoltaic systems offer a promising solution to reduce land use competition between food and energy production, fostering synergistic interactions that support sustainable land management and resource optimization [54–56].

Recent studies have extensively explored how shading from PV panels can impact the yields and quality parameters of crops. Photovoltaic shading has been shown to provide suitable microclimatic conditions, mitigating the adverse effects of excessive solar radiation and supporting crop health [57–59]. Crops that are not typically suited to high solar exposure may thrive better and yield higher nutritional values under PV shading [59]. While some high-light-demanding crops (potatoes, corn, tomatoes, cucumbers, sweet peppers) may experience limited yield reductions (<25%), crops with moderate light requirements (asparagus, ornamentals) often show no significant adverse effects. For instance, broccoli that was cultivated under agrivoltaics in South Korea showed a greener and more favorable appearance compared with open-field broccoli [60]. Hence, partial shading from agrivoltaic systems can be particularly beneficial for crops that respond positively to shading, such as medicinal and aromatic plants that are known for enhanced oil synthesis and bioactive compound production under shaded conditions [61,62]. In this study, the partial shading provided by agrivoltaic systems was observed to have differential effects on *Mentha arvensis* and *Mentha* × *piperita* varieties. However, in both mint types, the partial shading generally exhibited a positive impact on the plants' nutrient contents. Notably, *Mentha* × *piperita* showed a more pronounced response in terms of essential oil synthesis and the accumulation of bioactive compounds under shaded conditions. These findings suggest that even among varieties of the same plant species, the effectiveness of shading may vary, highlighting the need for cultivar-specific optimization in agrivoltaic applications.

The observed enhancement in nutrient uptake following AMF (*arbuscular mycorrhizal fungi*) inoculation can be attributed to several well-established mechanisms [63,64]. AMFs form symbiotic associations with plant roots, during which extraradical hyphae extend beyond the root zone and significantly increase the effective root surface area [65]. This expansion facilitates the absorption of relatively immobile nutrients such as phosphorus (P), zinc (Zn), and copper (Cu), especially under nutrient-limited conditions [66,67]. Moreover, AMF colonization alters the root architecture and modifies the biochemical properties of the rhizosphere, thus enhancing the enzymatic activity, adjusting the pH, and improving the solubilization and mobility of nutrients. Importantly, AMFs also contribute to improved plant–water interactions by enhancing the water uptake efficiency, which in turn supports nutrient transport and physiological processes in the roots [68]. These interactions can lead to the induction of stress-related phytohormones such as abscisic acid (ABA), helping plants cope better with abiotic stress conditions. In our study, such mechanisms probably contributed to the increased macro- and micronutrient concentrations that were observed in both *Mentha arvensis* and *Mentha* × *piperita*, particularly under the moderated microclimatic conditions that were created by photovoltaic (PV) panel shading. This suggests a synergistic interaction between AMF inoculation and agrivoltaic-induced shading, enhancing nutrient acquisition and thereby supporting improved plant performance and essential oil production.

According to our study results, cultivating mint species such as *Mentha arvensis* and *Mentha* × *piperita*, which are widely used in the pharmaceutical, cosmetic, and food industries, appears to be highly advantageous under photovoltaic systems. Partial shading conditions, further enhanced by mycorrhizal applications to form sustainable agricultural practices, positively impacted the yield and quality parameters of mint. The integration of agrivoltaics with sustainable soil management practices supports yield and quality improvements while preserving ecosystem balance [50]. Sustainable agrivoltaic management potentially resolves conflicts between photovoltaic installations and agriculture, particularly in ecologically fragile regions, enhancing climate resilience in crop production.

5. Conclusions

Agrivoltaic systems offer promising and integrative solutions by combining renewable energy production with sustainable crop cultivation. The shading effect of photovoltaic panels, when strategically managed, can enhance soil's moisture conservation and water use efficiency, particularly benefiting shade-tolerant or moderately light-demanding crops.

In this study, mycorrhizal inoculation significantly improved the performance of two mint species (*Mentha arvensis* and *Mentha* × *piperita*) when grown under agrivoltaic conditions. Notably, the highest fresh biomass yields for both species were recorded in between-panel (BP) areas with mycorrhizal treatment (PM1), while the lowest yields were observed in under-panel (UP) areas without inoculation (PAM0). Mycorrhizal application also enhanced macro- and micronutrient accumulation, including of N, P, K, Ca, Fe, Zn, and Mn, in both species. Furthermore, the essential oil yield peaked in *Mentha arvensis* under BP conditions with mycorrhiza (10.08%), whereas *Mentha* × *piperita* showed the highest essential oil content (4.50%) under UP conditions with mycorrhizal inoculation. While the composition of essential oil components differed between the species, overall improvements in both quantity and quality under mycorrhizal treatment were evident.

These findings highlight the synergistic potential of integrating mycorrhizal biotechnology into agrivoltaic systems to enhance the productivity and quality of crops in the context of sustainable agriculture. However, further research is required to fully understand and optimize these integrative strategies under diverse agroecological conditions. Future studies should prioritize long-term evaluations of soil health, including microbial dynamics, organic matter stability, and nutrient cycling, within agrivoltaic environments. Additionally, multi-crop trials involving species with differing light and water requirements could offer broader insights into the applicability and scalability of these systems. Assessing seasonal variability, crops' physiological responses, and the persistence of mycorrhizal benefits over time will also be essential for developing resilient and adaptive agrivoltaic models.

Author Contributions: Conceptualization, B.Ç.E. and M.T.E.; Methodology, B.Ç.E. and M.T.E.; Validation, B.Ç.E. and M.T.E.; Formal Analysis, B.Ç.E. and M.T.E.; Resources, M.E. and K.E.; Writing—Review and Editing, M.T.E., B.Ç.E., K.E. and M.E.; Visualization, B.Ç.E. and M.T.E.; Supervision, B.Ç.E.; Project Administration, M.T.E. and K.E. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by ENERJISA Enerji Üretim A.Ş., Türkiye, under the framework of sustainable development projects in renewable energy and agricultural integration.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors would like to extend their sincere appreciation to EnerjiSA Enerji Üretim A.Ş. for their financial support and providing the experimental site at Bandırma Agri-PV trial fields.

Conflicts of Interest: Authors Kaan Emir and Murat Eröz were employed by the company Enerjisa Enerji Üretim A.Ş. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Georgiou, A.; Skarlatos, D. Optimal site selection for sitting a solar park using multi-criteria decision analysis and geographical information systems. *Geosci. Instrum. Methods Data Syst.* **2016**, *5*, 321–332. [CrossRef]
2. Kabir, E.; Kumar, P.; Kumar, S.; Adelodun, A.; Kim, K. Solar energy: Potential and future prospects. *Renew. Sustain. Energy Rev.* **2018**, *82*, 894–900. [CrossRef]
3. Laasri, S.; El Hafidi, E.; Mortadi, A.; Chahid, E.G. Solar-powered single-stage distillation and complex conductivity analysis for sustainable domestic wastewater treatment. *Environ. Sci. Pollut. Res.* **2024**, *31*, 29321–29333. [CrossRef]
4. Blaydes, H.; Potts, S.G.; Whyatt, J.D.; Armstrong, A. Opportunities to enhance pollinator biodiversity in solar parks. *Renew. Sustain. Energy Rev.* **2021**, *145*, 111065. [CrossRef]
5. Tölgyesi, C.; Hábenczyus, A.A.; Kelemen, A.; Török, P.; Valkó, O.; Deák, B.; Bátori, Z. How to not trade water for carbon with tree planting in water-limited temperate biomes? *Sci. Total Environ.* **2023**, *856*, 158960. [CrossRef]
6. Walston, L.J.; Li, Y.; Hartmann, H.M.; Macknick, J.; Hanson, A.; Nootenboom, C.; Lonsdorf, E.; Hellmann, J. Modeling the ecosystem services of native vegetation management practices at solar energy facilities in the Midwestern. *United States Ecosyst. Serv.* **2021**, *47*, 101227. [CrossRef]
7. Delfanti, L.; Colantoni, A.; Recanatesi, F.; Bencardino, M.; Sateriano, A.; Zambon, I.; Salvati, L. Solar plants, environmental degradation and local socioeconomic contexts: A case study in a Mediterranean country. *Environ. Impact Assess. Rev.* **2016**, *61*, 88–93. [CrossRef]
8. Dinesh, H.; Pearce, J.M. The potential of agrivoltaic systems. *Renew. Sust. Energ. Rev.* **2016**, *54*, 299–308. [CrossRef]
9. Suuronen, A.; Muñoz-Escobar, C.; Lensu, A.; Kuitunen, M.; Celis, N.G.; Astudillo, P.E.; Ferrú, M.; Taucare-Ríos, A.; Miranda, M.; Kukkonen, J.V.K. The influence of solar power plants on microclimatic conditions and the biotic community in Chilean desert environments. *Environ. Manag.* **2017**, *60*, 630–642. [CrossRef]

10. Li, C.; Liu, J.; Bao, J.; Wu, T.; Chai, B. Effect of Light Heterogeneity Caused by Photovoltaic Panels on the Plant–Soil–Microbial System in Solar Park. *Land* **2023**, *12*, 367. [CrossRef]
11. Lafitte, A.; Sordello, R.; de Crespin de Billy, V.; Froidevaux, J.; Gourdain, P.; Kerbiriou, C.; Langridge, J.; Marx, G.; Schatz, B.; Thierry, C.; et al. What evidence exists regarding the effects of photovoltaic panels on biodiversity? A critical systematic map protocol. *Environ. Evid.* **2022**, *11*, 36. [CrossRef]
12. Gómez-Catasús, J.; Morales, B.; Giralt, D.; González Portillo, D.; Manzano-Rubio, R.; Solé-Bujalance, L.; Sardà-Palomera, F.; Traba, J.; Bota, G. Solar photovoltaic energy development and biodiversity conservation: Current knowledge and research gaps. *Conserv. Lett.* **2024**, *17*, e13025. [CrossRef]
13. Copetta, C.; Lingua, G.; Berta, G. Effects of three AM fungi on growth, distribution of glandular hairs, and essential oil production in *Ocimum basilicum* L. var. *Genovese*. *Mycorrhiza* **2016**, *16*, 485–494. [CrossRef]
14. Kapoor, R.; Chaudhary, V.; Bhatnagar, A.K. Effects of arbuscular mycorrhiza and phosphorus application on artemisinin concentration in *Artemisia annua* L. *Mycorrhiza* **2007**, *17*, 581–587. [CrossRef]
15. Gupta, M.L.; Prasad, A.; Ram, M.; Kumar, S. Effect of the vesicular–arbuscular mycorrhizal (VAM) fungus *Glomus fasciculatum* on the essential oil yield related characters and nutrient acquisition in the crops of different cultivars of menthol mint (*Mentha arvensis*) under field conditions. *Bioresour. Technol.* **2002**, *81*, 77–79. [CrossRef]
16. Kapoor, R.; Giri, B.; Mukerji, K.G. Improved growth and essential oil yield and quality in *Foeniculum vulgare* Mill on mycorrhizal inoculation supplemented with P-fertilizer. *Bioresour. Technol.* **2004**, *93*, 307–311. [CrossRef]
17. Khaosaad, T.; Vierheilig, H.; Nell, M.; Zitterl-Eglseer, K.; Novak, J. Arbuscular mycorrhiza alter the concentration of essential oils in oregano (*Origanum* sp., Lamiaceae). *Mycorrhiza* **2006**, *16*, 443–446. [CrossRef]
18. Russomanno, O.M.R.; Kruppa, P.C.; Minhoni, M.T.A. Infuência de fungos micorrízicos arbusculares no desenvolvimento de plantas de alecrim e manjericão. *Arq. Inst. Biol.* **2008**, *75*, 37–43. [CrossRef]
19. Zubek, S.; Błaszkowski, J. Medicinal plants as hosts of arbuscular mycorrhizal fungi and dark septate endophytes. *Phytochem. Rev.* **2009**, *8*, 571–580. [CrossRef]
20. Zubek, S.; Stojakowska, A.; Anielska, T.; Turnau, K. Arbuscular mycorrhizal fungi alter thymol derivative contents of *Inula ensifolia* L. *Mycorrhiza* **2010**, *20*, 497–504. [CrossRef]
21. Binet, M.N.; Van Tuinen, D.; Deprêtre, N.; Koszela, N.; Chambon, C.; Gianinazzi, S. Arbuscular mycorrhizal fungi associated with *Artemisia umbelliformis* Lam, an endangered aromatic species in Southern French Alps, influence plant P and essential oil contents. *Mycorrhiza* **2011**, *21*, 523–535. [CrossRef]
22. Arango, M.C.; Ruscitti, M.F.; Ronco, M.G.; Beltrano, J. Mycorrhizal fungi inoculation and phosphorus fertilizer on growth, essential oil production and nutrient uptake in peppermint (*Mentha piperita* L.). *Rev. Bras. Plantas Med.* **2012**, *14*, 692–699. [CrossRef]
23. Beigi, M.; Torki-Harchegani, M.; Ghasemi Pirbalouti, A. Quantity and chemical composition of essential oil of peppermint (*Mentha* × *piperita* L.) leaves under different drying methods. *Int. J. Food Prop.* **2018**, *12*, 267–276. [CrossRef]
24. Mint Essential Oils Market Report. 2025. Available online: https://www.researchandmarkets.com/report/mint-oil?srsltid (accessed on 31 May 2025).
25. Yilmaz, K.; Telci, I. Yield and oil composition of peppermint cultivars grown in the Isparta climate of Turkey. *Turk. J. Agric. For.* **2022**, *46*, 10. [CrossRef]
26. Süntar, I. Importance of ethnopharmacological studies in drug discovery: Role of medicinal plants. *Phytochem. Rev.* **2020**, *19*, 1199–1209. [CrossRef]
27. Li, Y.; Kong, D.; Fu, Y.; Sussman, M.R.; Wu, H. The effect of developmental and environmental factors on secondary metabolites in medicinal plants. *Plant Physiol. Biochem.* **2020**, *148*, 80–89. [CrossRef]
28. Wei, H.; Kong, S.; Jayaraman, V.; Selvaraj, D.; Soundararajan, P.; Manivannan, A. *Mentha arvensis* and *Mentha* × *piperita*-Vital Herbs with Myriads of Pharmaceutical Benefits. *Horticulturae* **2023**, *9*, 224. [CrossRef]
29. Temel, M.; Tınmaz, A.B.; Oztürk, M.; Gündüz, O. Production and Trade of Medicinal and Aromatic Plants in the World and Turkey. *KSU J. Agric. Nat.* **2018**, *21*, 198–214. [CrossRef]
30. Fortune Business Insights. Mint Oils Market Size, Share & Industry Analysis, by Application (Oral Products, Confectionary Products, Pharmaceutical Products, Tobacco Products, Fragrance Products, and Others), and Regional Forecast, 2025–2032. 2024. Available online: http://www.fortunebusinessinsights.com/mint-oils-market-104220 (accessed on 11 May 2025).
31. Hudz, N.; Kobylinska, L.; Pokajewicz, K.; Horčinová Sedláčková, V.; Fedin, R.; Voloshyn, M.; Myskiv, I.; Brindza, J.; Wieczorek, P.P.; Lipok, J. *Mentha piperita*: Essential Oil and Extracts, Their Biological Activities, and Perspectives on the Development of New Medicinal and Cosmetic Products. *Molecules* **2023**, *28*, 7444. [CrossRef]
32. Ozguven, M.; Kırıcı, S. Research on yield, essential oil, contents and components of mint (mentha) species in different ecologies. *Turk. J. Agric. For.* **1999**, *23*, 465–472.
33. Kumar, A.; Shukla, R.; Singh, P.; Singh, A.K.; Dubey, N.K. Use of essential oil from *Mentha arvensis* L. to control storage moulds and insects in stored chickpea. *J. Sci. Food Agric.* **2010**, *89*, 2643–2649. [CrossRef]

34. Skalicka-Woźniak, K.; Walasek, M. Preparative separation of menthol and pulegone from peppermint oil (*Mentha piperita* L.) by high-performance counter-current chromatography. *Phytochem. Lett.* **2014**, *10*, 94–98. [CrossRef]
35. Grulova, D.; De Martino, L.; Mancini, E.; Salamon, I.; De Feo, V. Seasonal variability of the main components in essential oil of *Mentha* × *piperita* L. *J. Sci. Food Agric.* **2015**, *95*, 621–627. [CrossRef]
36. Oliveira Santos, G.A.; Matos Jorge, R.M.; Oliveira Farias, F.; Mathias, A.L. Perspective on the Use of Agrivoltaic Systems for the Production of Secondary Metabolites Applicable to Food: The Case for Mint. *Braz. Arch. Biol. Technol.* **2024**, *67*, e24240160. [CrossRef]
37. De Francesco, C.; Centorame, L.; Toscano, G.; Duca, D. Opportunities, Technological Challenges and Monitoring Approaches in Agrivoltaic Systems for Sustainable Management. *Sustainability* **2025**, *17*, 634. [CrossRef]
38. Valle, B.; Simonneau, T.; Sourd, F.; Pechier, P.; Hamard, P.; Frisson, T.; Rychewaert, M.; Christophe, A. Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops. *Appl. Energy* **2017**, *206*, 1495–1507. [CrossRef]
39. Meteoblue. Available online: https://www.meteoblue.com (accessed on 24 March 2025).
40. Kacar, B. *Physical and Chemical Soil Analysis*; Nobel Publications and Distribution: Ankara, Türkiye, 2016.
41. Van Reeuwijk, L.P. *Procedures for Soil Analysis*, 6th ed.; Technical Paper No. 9; FAO/ISRIC: Wageningen, The Netherlands, 2002; 120p.
42. Bremner, J.M. Total nitrogen. In *Methods of Soil Analysis: Part 2. Chemical and Microbiological Properties*; Black, C.A., Ed.; American Society of Agronomy, Inc.: Madison, WI, USA, 1965; pp. 1149–1178.
43. Kacar, B.; İnal, A. *Plant Analyses*; Nobel Publishing: Ankara, Türkiye, 2008.
44. Harborne, J.B. *Phytochemical Methods*, 2nd ed.; Chapman and Hall: New York, NY, USA, 1984. [CrossRef]
45. Mrlianova, M.; Tekelova, D.; Felklova, M.; Toth, J.; Musil, P.; Grancai, D. Comparison of the quality of *Melissa officinalis* L. cultivar citra with mellissas of european origin. *Ceska Slov. Farm.* **2001**, *50*, 299–302.
46. Council of Europe. *European Pharmacopoeia*, 3rd ed.; Council of Europe: Strasbourg, France, 1997. Available online: https://openlibrary.org/books/OL20075393M/ (accessed on 17 April 2025).
47. Adams, R.P. *Identification of Essential Oils Components by Gas Cromatigraphy/Mass Spectroscopy*; Allured Publishing Corporation: Carol Stream, IL, USA, 1995.
48. Ozturk, B.; Konyalioglu, S.; Kantarcı, G.; Cetinkol, D. Essential oil composition, antibacterial antifungal and antioxidant capacity of wild *Lavandula stoechas* L. subsp. stoechas from Izmir. *Anadolu JAARI* **2005**, *15*, 61–72.
49. Jamil, F.; Ali, H.M.; Nasir, M.A.; Karahan, M.; Janjua, M.M.; Naseer, A.; Pasha, R.A. Evaluation of photovoltaic panels using different nano phase change material and a concise comparison: An experimental study. *Renew. Energy* **2021**, *169*, 1265–1279. [CrossRef]
50. Luo, J.; Luo, Z.; Li, W.; Shi, W.; Sui, X. The Early Effects of an Agrivoltaic System within a Different Crop Cultivation on Soil Quality in Dry–Hot Valley Eco-Fragile Areas. *Agronomy* **2024**, *14*, 584. [CrossRef]
51. Disciglio, G.; Frabboni, L.; Tarantino, A.; Stasi, A. Association between Dynamic Agrivoltaic System and Cultivation: Viability, Yields and Qualitative Assessment of Medical Plants. *Sustainability* **2023**, *15*, 16252. [CrossRef]
52. Ram, M.; Kumar, S. Yield and resource use optimization in late transplanted mint (*Mentha arvensis*) under sub-tropical conditions. *J. Agron. Crop Sci.* **1998**, *180*, 109–112. [CrossRef]
53. Giri, N.C.; Mohanty, R.C. Design of Agrivoltaic System to Optimize Land Use for Clean Energy-Food Production: A Socio-Economic and Environmental Assessment. *Clean. Technol. Environ. Policy* **2022**, *24*, 2595–2606. [CrossRef]
54. Ferrante, A.; Marian, L. Agronomic management for enhancing plant tolerance to abiotic stresses: High and low values of temperature, light intensity, and relative humidity. *Horticulturae* **2018**, *4*, 21. [CrossRef]
55. Yasoda, P.G.C.; Pradheeban, L.; Nishanthan, K.; Sivachandiran, S. Effect of Different Shade Levels on Growth and Yield Performances of Cauliflower. *Int. J. Environ. Agric. Biotechnol.* **2018**, *3*, 948–955. [CrossRef]
56. Ferreira, R.F.; Marques Lameirinhas, R.A.; Bernardo, C.P.C.V.; João, J.P.; Santos, M. Agri-PV in Portugal: How to Combine Agriculture and Photovoltaic Production. *Energy Sustain. Dev.* **2024**, *79*, 101408. [CrossRef]
57. Sekiyama, T.; Nagashima, A. Solar sharing for both food and clean energy production: Performance of agrivoltaic systems for corn, a typical shade-intolerant crop. *Environments* **2019**, *6*, 65. [CrossRef]
58. Weselek, A.; Bauerle, A.; Zikeli, S.; Lewandowski, I.; Högy, P. Effects on crop development, yields and chemical composition of celeriac (*Apium graveolens* L. var. *rapaceum*) Cultivated Underneath an Agrivoltaic System. *Agronomy* **2021**, *11*, 733. [CrossRef]
59. Harold, S. Photovoltaics alter plant productivity. *Nat. Ecol. Evol.* **2023**, *7*, 494. [CrossRef]
60. Chae, S.-H.; Kim, H.J.; Moon, H.-W.; Kim, Y.H.; Ku, K.-M. Agrivoltaic Systems Enhance Farmers' Profits through Broccoli Visual Quality and Electricity Production without Dramatic Changes in Yield, Antioxidant Capacity, and Glucosinolates. *Agronomy* **2022**, *12*, 1415. [CrossRef]
61. Giardini, L. *Agronomia Generale, Ambientale ve Aziendale*; Scienza E Tecniche Delle Produz. Vegetali: Bologne, Italia, 1992; p. 600.
62. Ilić, S.Z.; Milenković, L.; Šunić, L.; Tmušić, N.; Mastilović, J.; Kevrešan, Ž.; Stanojević, L.; Danilović, B.; Stanojević, J. Efficiency of basil essential oil antimicrobial agents under different shading treatments and harvest times. *Agronomy* **2021**, *11*, 1574. [CrossRef]

63. Fokom, R.; Adamou, S.; Essono, D.; Ngwasiri, D.P.; Eke, P.; Mofor, C.T.; Tchoumbougnang, F.; Fekam, B.F.; Zollo, P.H.A.; Nwaga, D.; et al. Growth, essential oil content, chemical composition and antioxidant properties of lemongrass as affected by harvest period and arbuscular mycorrhizal fungi in field conditions. *Ind. Crops Prod.* **2019**, *138*, 111477. [CrossRef]
64. Kaba, J.S.; Abunyewa, A.A.; Kugbe, J.; Kwashie, G.K.S.; Ansah, E.O.; Andoh, H. Arbuscular mycorrhizal fungi and potassium fertilizer as plant biostimulants and alternative research for enhancing plants adaptation to drought stress: Opportunities for enhancing drought tolerance in cocoa (*Theobroma cacao* L.). *Sustain. Environ.* **2021**, *7*, 1963927. [CrossRef]
65. Wen, Z.; Chen, Y.; Liu, Z.; Meng, J. Biochar and arbuscular mycorrhizal fungi stimulate rice root growth strategy and soil nutrient availability. *Eur. J. Soil. Biol.* **2022**, *113*, 103448. [CrossRef]
66. Gupta, M.M. Arbuscular mycorrhizal fungi: The potential soil health indicators. In *Soil Health*; Giri, B., Varma, A., Eds.; Springer: Cham, Switzerland, 2020; pp. 183–195.
67. Duan, J.; Tian, H.; Drijber, R.A.; Gao, Y. Systemic and local regulation of phosphate and nitrogen transporter genes by arbuscular mycorrhizal fungi in roots of winter wheat (*Triticum aestivum* L.). *Plant Physiol. Biochem.* **2015**, *96*, 199–208. [CrossRef]
68. Hazzoumi, Z.; Moustakime, Y.; Joutei, K.A. Effect of arbuscular mycorrhizal fungi (AMF) and water stress on growth, phenolic compounds, glandular hairs, and yield of essential oil in basil (*Ocimum gratissimum* L.). *Chem. Biol. Technol. Agric.* **2015**, *2*, 10. [CrossRef]