



The effect of transparent agri-photovoltaics and multifunctional netting system on raspberry yield and quality

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ABSTRACT

Agri-photovoltaic (AgriPV) systems integrate solar energy generation with crop production, offering dual land-use benefits in regions that are facing land scarcity and climate challenges due to temperature extremes. This study assessed the impact of an AgriPV installation on the performance of a primocane red raspberry (*Rubus idaeus* L.) cultivar under Mediterranean conditions. Specifically, three production systems were assessed: (1) AgriPV and white net, (2) white net alone, and (3) open field (unprotected cultivation). Yield, plant growth parameters, and microclimate conditions were monitored throughout the primo-cane production season, spanning from early August until mid-November. In addition, fruit from three distinct harvestings were monitored for polyphenolic composition and aroma profile. Results indicated a substantial yield increase of 65% under AgriPV and white net combination compared to open field. The yield increase was less pronounced when white net alone was placed above the plantation. The increase was particularly evident when excessive air temperatures were monitored and is attributed to the favourable microclimate created by plant shading during temperature extremes that additionally resulted in enhanced water use efficiency. A significant impact of the different production systems was recorded mainly in sugar-related fruit attributes, while limited variation on other secondary metabolites was monitored. In particular, total soluble sugars (TSS) content was generally higher under the AgriPV and netting system at all harvest points. Liquid Chromatography–Mass Spectrometry (LC-MS) analysis led to the identification and quantification of 16 polyphenolic compounds in raspberry fruits. The most prevalent compounds in all timepoints were cyanidin's derivatives. Volatile organic compounds (VOCs) composition was more strongly affected by the harvest period than by the cultivation conditions, indicating a developmentally driven aroma evolution. Overall, results reported herein demonstrate an evident advantage of AgriPV's viability under harsh environmental conditions for raspberry production, without any trade-offs in qualitative and/or sensorial attributes.

1. Introduction

Red raspberry (*Rubus idaeus* L.) is a widely cultivated crop of growing economic significance. Driven by rising consumer demand, global production has surpassed 956.000 tons in 2023 (FAOSTAT). This surge

highlights its high market value, export potential as well as the significant resources, technical expertise, and investments required to maintain production demand [1].

Berry fruits are recognised as a “superfood” due to their high fibre content and abundance of bioactive phytochemicals, such as

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anthocyanins and ellagitannins. These compounds exhibit antioxidant, anti-inflammatory, and metabolic-stabilizing effects, which are linked with improved cardiovascular health, glycemic control, vascular function, and neuroprotection [2,3]. Health promoting benefits of raspberries have further boosted their popularity among health-conscious consumers and researchers, as part of different dietary strategies to reduce chronic disease risk [2,4].

Raspberries are split in two main cultivar groups: once-fruiting (floricanes), which fruit annually on second year canes, and repeat-fruiting (primocane), which produce an additional fruit crop on primocanes in the late summer or fall. Primocane fruiting extends the harvest, resulting in higher yields [5,6]. Optimal growth for raspberries requires moderate air (18–21 °C) and soil (24–27 °C) temperatures whereas excessive heat suppresses photosynthesis, reducing plant vigor and fruit size [7]. Although tolerant to cold and drought conditions, raspberries are particularly susceptible to high temperatures, presenting a major limitation under climate extremes [8]. The optimal photosynthetically active radiation (PAR) for raspberry is about 500–700 $\mu\text{mol m}^{-2} \text{s}^{-1}$ depending on the cultivar, agronomic practices and climatic condition [9]. However, it is well known that vapor pressure deficit (VPD) can cause a physiological damage in several species when it exceeds 2 kPa.

To meet the growing demand of raspberries, Mediterranean regions characterized by mild winters and warm, dry summers, have been explored. However, most primocane-fruiting cultivars, developed for cooler temperate environments, often show reduced yield and fruit quality under warmer conditions [10]. Mild winters may limit the chilling accumulation that is required for proper dormancy and flowering while elevated temperatures induce heat stress. Although new primocane cultivars that do not require chilling, have improved year-round production potential, vulnerability to high temperatures remains significant [11].

Cyprus represents a clear example of these climatic challenges. Located in the Mediterranean region, the island experiences a semi-arid to Mediterranean climate (BSH according to Köppen's classification, [12]), with mean annual temperatures of approximately 18–20 °C in lowland areas, summer maximum temperatures regularly exceeding 40 °C, mean annual precipitation below 500 mm (ranging from <300 mm in coastal lowlands to ~1000 mm in the Troodos Mountain range), and uneven seasonal distribution. The experimental site was located in Chandria (Limassol District) at 1250 m above sea level, where summer air temperatures can reach 35 °C and peak incoming solar radiation regularly exceeds 800 W/m². As one of the most challenging environments for agriculture in Europe, it experiences a range of climates, from temperate mountain conditions to hot, arid lowlands as well as uneven and low annual precipitation [12–16]. These climatic constraints limit traditional open field berry cultivation, as heat stress reduces berry size, yield, and fruit quality [7]. While production is expanding in mountainous regions with cooler conditions, extreme summer heat episodes disrupt floral induction leading to abnormal fruits and limited yield.

To alleviate negative environmental impact, the use of multifunctional netting systems in agriculture is increasing. Such systems protect crops from a variety of abiotic and biotic stressors while it has been reported the potential to improve canopy microclimate, enhance vegetative growth and increase fruit weight in certain crops like table olive cultivars preserve fruit quality by reducing hail damage, sunburn, soil temperature and wind [17]. The deployment of shading structures especially “aluminet” materials (plastic or net) physically intercepting a calculated fraction of the incoming shortwave solar radiation, shading nets significantly reduce the thermal energy reaching the plant canopy. This directly lowers the leaf surface temperature, often bringing it back within the optimal thermal kinetic window for Rubisco enzyme activity [18].

Simultaneously, the agricultural sector is undergoing a major shift due to the global transition towards renewable energy. Rising

greenhouse gas emissions (GHG) rendered inevitable the shift to renewable energy sources [19]. Policies such as the European Green Deal and ‘Fit for 55’ are accelerating energy sector decarbonization, with solar energy as the fastest-growing energy source. A record 602 GW of solar photovoltaic (PV) capacity was added in 2024, bringing global cumulative capacity to 2.25 TW by early 2025 [20]. To achieve climate targets, global solar deployment must reach around 1 TW of new capacity annually, with the EU targeting nearly 600 GW by 2030 [21]. This expansion requires extensive land conversion-over 12,000 km²-raising concerns about land competition, especially in protected or high-value agricultural areas [22].

To address these land-use conflicts, agri-photovoltaic (AgriPV) system, where PV generation is co-located with agriculture, have emerged as a leading dual-use land strategy. AgriPV aims to align energy deployment with continued agricultural production, supporting clean energy goals while safeguarding biodiversity and food security. Beyond improving land-use efficiency, PV module integration provides physical protection, reduces thermal stress and fruit damage, improves water-use efficiency, and optimizes light conditions particularly relevant for temperate orchards and shade- or heat-sensitive crops such as raspberries [23,24]. Partial shading from AgriPV can shield plants from extreme weather, enhance resilience, and even boost yields. Recent studies, though limited, indicate that AgriPV can positively affect raspberry production, with reports of increased yields and water savings under PV compared to conventional tunnels [25,26], as well as evidence of potential opportunities for raspberry cultivation [27,28]. Additional case studies across i.e. BayWa (<https://www.baywa.com/en/about/electricity-heating-mobility/europes-largest-fruitvoltaic-project>) support these findings, showing reduced weather-related losses and stable or improved yields despite climate extremes.

While research on AgriPV and raspberries is still emerging, a broader literature exists for other berry crops (e.g., strawberries, blueberries, blackberries) under PV [29–32]. Many studies report that berries benefit from shading, with positive yield effects up to 60% shade [33], increased growth in blackberries [34], and improved blueberry yields under moderate shade [29]. However, results are often contradictory, while excessive shading can reduce yields [35] according to a physiological threshold of 30% shading to avoid strong yield reduction in fruit orchards in temperate climatic conditions [36]. Such observations highlight the need for dynamic or adjustable shading strategies [21].

Given the considerable knowledge gap in understanding raspberry crop response to PV shading [29,37], this study examined AgriPV shading effects on plant physiology and crop productivity of raspberry plants in Southern Europe, using a mountainous location in Cyprus, that is characterized by temperature extremes during summer. To test this hypothesis, the present study aimed to: (i) quantify microclimate modifications induced by AgriPV and netting systems; (ii) evaluate plant physiological responses and yield performance across the whole primocane season; and (iii) assess the impact of different cultivation systems on fruit quality attributes, polyphenolic composition, and aroma profile at multiple harvest timepoints.

2. Materials and methods

2.1. AgriPV and netting system design and installation

To design the AgriPV systems, recent innovations were initially reviewed and evaluated to select a solution capable of providing precise and reliable modulation of PV transparency, thereby optimizing light conditions for crop growth. In parallel, several innovative structural concepts for the PV canopy were investigated. Based on the identified requirements, an overhead PV Bifacial Agri-PV Solar Panel | Green-Glass™ mounting structure (BSG-300/54-F, Brite Solar, Thessaloniki, Greece) was selected for the needs of the current study.

In addition, the use of a net at the pilot site was considered to enable controlled regulation of light exposure and to provide protection against

insects and temperature extremes. Consequently, a netting system was tailored to an average shading not higher than 15%. In particular, an anti-insect net in high density polyethylene (HDPE) “Monotex 50” (Agritech, Eboli, Italy) of white (neutral) colour, mesh size of 0.97×1.54 mm and weight of 95 g m^{-2} was used for the field trials.

Overall, three production systems were compared: (i) AgriPV with a white net installed below the PV cover (AgriPV & WN), (ii) White Net (WN), and (iii) Open Field (OF) for a total of 290 m^2 . The AgriPV system was installed in Chandria ($34^{\circ}56'18.26''\text{N}$ $32^{\circ}59'54.67''\text{E}$, Limassol District, Cyprus), with PV modules and the netting system mounted over the designated area. The selected semi-transparent PV modules were elevated at a 3.5 m height, just 1 m above the crops on metal supports, forming PV canopies that enable both PV power generation and crop protection beneath (Fig. 1).

2.2. Plant material and treatments

Young rooted plants of red raspberry (*Rubus idaeus* L. cv. ‘Wengi’) were initially received as tray plants in Cyprus on 14 May 2024. The plants were transplanted into 10 L pots filled with 100% fine coco-coir

buffered with calcium nitrate on 30 May 2024, which was considered as 0 days after planting (DAP). The raspberry plantation was established in two neighbouring plots located at 1250 m above sea level. The planting rows were oriented from south to north, and the plants were cultivated in pots under an open greenhouse structure. All crops received standard horticultural management practices, including drip irrigation, and fertigation was adjusted to the plants' phenological stages. Before the installation of the AgriPV system, two harvest cycles were completed. At the beginning of the AgriPV experimental period, the plants had re-entered the flowering stage. More precisely, plants received 1 mS/cm during flowering, 2 mS/cm at the vegetative stage and 1.5 mS/cm at the fruiting stage.

The experimental design consisted of four spatially separated blocks. Each block included nine uniformly grown plants arranged in linear rows. Each row was oriented from south to north and had a spacing of 1.8 m between each rows. Each block was separated with a buffer of 1.5 m within rows as schematically represented in Fig. 1. All plants were irrigated using on line drippers that distribute 4 L/h/pot with spider and arrow emitters. From March until May and from October until November 2025, plants were irrigated with 3 intervals per day of 10 min

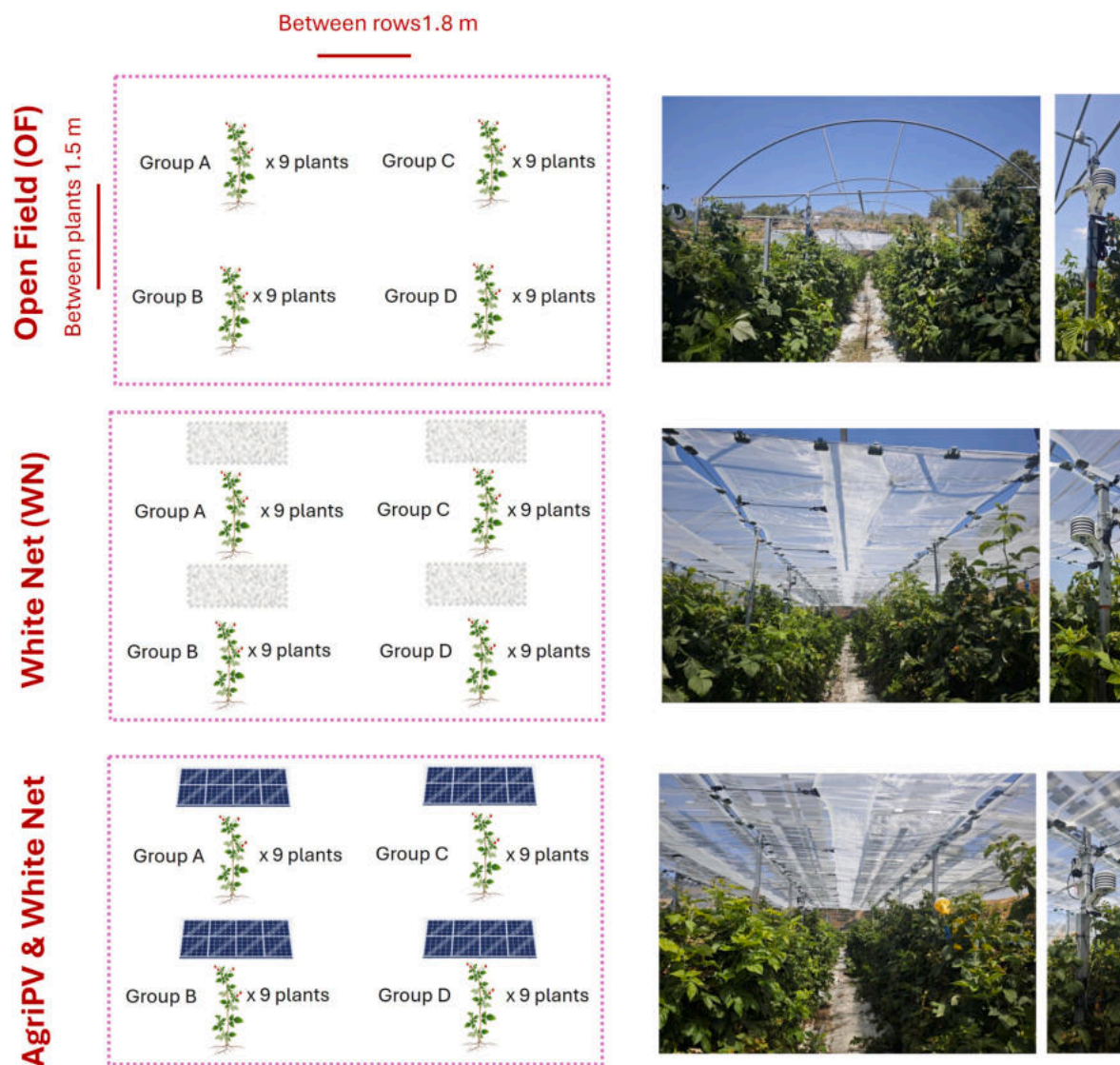


Fig. 1. Illustration of the experimental design conducted throughout the growing season in a raspberry field trial. Plants were grown under three cultivation systems: open field (OF), white net (WN), and an AgriPV system combined with white net (AgriPV & WN). For each treatment, plants were arranged in four blocks (A–D), with nine plants per block. Each block served as a biological replicate. Blocks were spaced 1.5 m apart within rows, while a distance of 1.8 m was maintained between rows.

and 4L/h, while from May until September, plants received 4 intervals per day, of 15 min. Therefore, each pot (plant root) received a total of 780 L during the season. Water use efficiency (WUE) measures the amount of primocane fruits (g) produced per L of water used. WUE was calculated by the dividing yield ($\text{g} \cdot \text{plant}^{-1}$) in each treatment by the total amount of water applied ($\text{L} \cdot \text{plant}^{-1}$) [38].

2.3. Sensing equipment, weather station and monitoring platform

The prevailing meteorological and microclimatic conditions were monitored at canopy and crop level using an integrated weather station. The station included microclimate sensors, positioned at plant height in both shaded and reference zones, along with an additional sensor for incident global horizontal irradiance (Watts/m^2) above the PV canopy. In particular, shielded temperature–humidity probes within the station recorded air temperature ($^{\circ}\text{C}$) and relative humidity (%) in the plant canopy under the PV structure and in the reference area. Soil or substrate moisture was logged using volumetric water content sensors with an automated alert system if they went below 10% and above 25% inserted into two representative pots of each treatment to ensure comparable irrigation status. All sensors were connected to a central data-acquisition system with synchronized timestamps, and field data were stored for subsequent analysis of the coupled energy–crop performance.

2.4. Yield, agronomic and physiological measurements

Full season primocane yield per plant was monitored from August 2 (429 DAP) to November 20 (539 DAP) in 2025. Cumulative yield was calculated as fresh fruit weight (g) per plant. In addition, berry number and berry length were recorded at each harvest to calculate average berry weight (g) per plant and average berry length (cm) per plant. These yield-related indices were derived from a total of forty-two harvests conducted throughout the growing season across the three different production systems.

Physiological measurements were conducted at 4 different time-points during the growing season (August 1, August 22, September 28 and October 30 in 2025 corresponding to 428, 449, 486 and 518 DAP, respectively). At each sampling date, thirty-six measurements per treatment were obtained using the LI-600 Porometer/Fluorometer (LI-COR, USA), Normalized Difference Vegetation Index (NDVI) sensor and SPAD meter following established protocols described in previous studies [39,40]. Measurements were taken from individual plants, with nine plants per block representing one biological replication. Stomatal conductance ($\text{mol m}^{-2} \text{s}^{-1}$) and transpiration rate ($\text{mmol m}^{-2} \text{s}^{-1}$) were determined. Chlorophyll fluorescence under ambient light conditions to determine the effective quantum efficiency in light (PhiPS2) was monitored. Electron transport rate (ETR; $\mu\text{mol m}^{-2} \text{s}^{-1}$) Leaf vapor pressure deficit atmosphere (VPD_{leaf}; kPa), leaf temperature ($^{\circ}\text{C}$), and photosynthetically active radiation (PAR, Qamb; $\mu\text{mol photons m}^{-2} \text{s}^{-1}$) were additionally recorded. Crop vigor was assessed through Normalized Difference Vegetation Index (NDVI), using a handheld GreenSeeker proximal crop sensor (Trimble Inc., Sunnyvale, CA, USA). Measurements were conducted at approximately 0.3 m above the plant canopy.

Leaf chlorophyll content was assessed using a handheld SPAD-502Plus chlorophyll meter (Konica Minolta Inc., Japan). The device measures absorbance at wavelengths of 650 and 940 nm over a sensing area of 2 mm × 3 mm, enabling measurements on small leaves up to 1.2 mm thick.

2.5. Fruit quality attributes

2.5.1. Soluble Solid Content (SSC), Titratable Acidity (TA) and Ripening Index (RI)

Quality attributes were determined in 3 distinct harvesting dates (August 20, September 10, and September 24 in 2025 corresponding to 447, 468 and 482 DAP, respectively). Approximately 200 g of

raspberries were collected per biological replicate from each treatment and immediately transported to the laboratory. Half of the sampled material (100 g) was rapidly frozen in liquid nitrogen and stored at -80°C for subsequent analyses, while the remaining portion was processed fresh.

Fresh samples were homogenized for 1–2 min using an IKA® T25 digital ULTRA-TURRAX® homogenizer and transferred into 50 mL Falcon tubes. The resulting homogenate was centrifuged (Sigma 4K15, Germany) at 21,190 g for 10 min at 4°C , after which the supernatant was recovered. This extract was initially used for the determination of soluble solid content (SSC) and total acidity (TA) and subsequently stored at -20°C until further biochemical analyses.

SSC was measured using a digital refractometer (Atago PR-32α, Japan), and values were expressed in °Brix. TA was determined with an automated multi-position titration system (862 Compact Titrator, Metrohm AG, Switzerland). For titration, 1 mL of diluted juice was combined with 49 mL of distilled water and titrated with 0.1 N NaOH to an endpoint pH of 8.1. Total acidity was expressed as percentage (%) of citric acid equivalents. The ripening index (RI) was calculated as the ratio of SSC to TA.

2.5.2. Total soluble sugars, sucrose, glucose, fructose content

Total soluble sugars (TSS), including sucrose, glucose, and fructose, were extracted following the protocol described by Hadjipieri et al. [41], with minor adjustments. Briefly, 0.3 g of raspberry tissue was extracted using 15 mL of 80% (v/v) ethanol. Sugar concentrations were subsequently quantified by spectrophotometric analysis according to previously established methods [42,43].

2.5.3. Quantification of total phenolic, anthocyanin and flavonoid content

Previously flash-frozen raspberry fruits were homogenized to a fine powder using a basic A11 analytical mill (IKA Mills) in the presence of liquid nitrogen. The extraction of total phenolic compounds was performed following the method of Shehata et al. [44], with minor modifications. Specifically, 0.05 g of the powdered sample was mixed with 1.5 mL of 50% (v/v) methanol and vortexed thoroughly. The mixtures were then incubated at -20°C for 24 h. Samples were subsequently centrifuged at 16,000 g for 10 min at 4°C using an Eppendorf Centrifuge 5415 R, and the supernatants were collected and stored at -20°C until analysis. Total phenolic content was determined using a modified Folin–Ciocalteu assay as described by Georgiadou et al. [45]. The reaction mixture consisted of 100 μL of appropriately diluted 50% v/v methanolic extract, 0.5 mL of distilled water, and 0.05 mL of Folin–Ciocalteu reagent. After a 3 min incubation, 0.1 mL of saturated sodium carbonate solution was added, and the final volume was adjusted to 1 mL with distilled water. The samples were mixed thoroughly and incubated for 1 h at room temperature in the dark, after which absorbance was measured at 765 nm. All measurements were performed in triplicate, and results were expressed as mg gallic acid equivalents (GAE) per 100 g fresh weight.

Total anthocyanins were extracted according to the method described by Bal and Ürün [46], with minor modifications. Briefly, 0.1 g of frozen raspberry tissue, previously ground to a fine powder, was combined with 1 mL of 95% v/v ethanol: 0.1 N HCl (85:15) and vortex-mixed thoroughly. The samples were then incubated at -20°C for 24 h, followed by centrifugation at 16,000 g for 10 min at 4°C using an Eppendorf Centrifuge 5415 R. The supernatants were collected and stored at -20°C until analysis. Total anthocyanin content was quantified using the pH differential method, employing two buffer systems: potassium chloride buffer (0.025 M, pH 1.0) and sodium acetate buffer (0.4 M, pH 4.5), as described by Georgiadou et al. [45]. Samples were diluted separately in each buffer, and absorbance readings were recorded at 510 and 700 nm. Anthocyanin concentration was calculated and expressed as mg cyanidin-3-glucoside per 100 g fresh weight.

Total flavonoid content was determined following the protocol of Meyers et al. [47], with minor adaptations. Briefly, 1 g of frozen

raspberry tissue, previously ground to a fine powder, was extracted with 10 mL of acetone and vortex-mixed thoroughly. The extracts were then incubated at -20°C for 24 h. After incubation, samples were centrifuged at 16,000 g for 10 min at 4°C using an Eppendorf Centrifuge 5415 R, and the supernatants were collected and stored at -20°C until analysis. Flavonoid concentration was quantified using a colorimetric assay based on the method of Chang et al. [48], with slight modifications. The reaction mixture consisted of 0.5 mL of plant extract, 1.5 mL of 95% (v/v) ethanol, 0.1 mL of 10% (w/v) aluminum chloride, 0.1 mL of 1 M potassium acetate, and 2.8 mL of distilled water. Following incubation at room temperature for 30 min, absorbance was recorded at 415 nm. Total flavonoid content was expressed as mg quercetin equivalents per 100 g fresh weight.

2.5.4. Polyphenolic compound analysis

The determination of polyphenolic compound's presence was performed by HPLC-DAD-ESI-MS/MS system as elsewhere described [49]. Phenolics identification and quantification were carried out on an Agilent 1100 HPLC system equipped with a photodiode array detector (G1315D) and coupled in series to an HCT Ultra Bruker Daltonics ion trap mass spectrometer through an electrospray ionization (ESI) interface HPLC-DAD-ESI-MS/MS. The compounds' separation was achieved on a Poroshell 120 EC column (3×100 mm, $2.7\ \mu\text{m}$) from Agilent Technologies (Waldbronn, Germany). Phenolic compounds were identified by their UV spectra, retention time, molecular weight, and MS/MS fragmentation pattern. p-Coumaric acid (320 nm), cyanin and cyanidin (520 nm), kaempferol and quercetin (360 nm), catechin (280 nm), ellagic acid (360 nm), and apigenin (340 nm) were used as standards to quantify hydroxycinnamic acid derivatives, anthocyanins, flavonols, flavan-3-ols, ellagic acid conjugates and flavones, respectively.

2.5.5. Volatile organic compounds

The determination of the volatile compounds was performed by a Shimadzu GCMS-QP2010 Plus System, operated using a method previously described [49]. Briefly, 5 g of frozen powdered raspberry fruit tissue was mixed with 5 mL of 1 M NaCl solution. The mixture was homogenized and samples were stored at -80°C until further analysis. Prior to the analysis, samples were transferred to a headspace vial (20 mL) and incubated in a water bath (40°C) for 35 min. After the incubation, the volatile compounds were extracted by SPME fiber (50/30 μm DVB/CAR/PDMS, Stableflex (2 cm), 23Ga) for 40 min immediately after the 40 min of extraction, the SPME fibre was injected manually into the inlet of the GC-MS.

The volatile organic compounds (VOCs)' separation in the GC-MS system was performed by GL Sciences InertCap 5MS 30 m - $0.25\ \mu\text{m}$ film thickness capillary column. Helium (He) was used as carrier gas ($1.2\ \text{mL/min}$) at high purity. The samples were injected manually in splitless mode. The injection temperature was set at 250°C . The oven was programmed as follows: hold at 35°C for 5 min, increase to 150°C in 4°C/min increments, then to 240°C in 50°C/min increments. The temperature remained at 240°C for 5 min. The MS Detector operated in EI mode (full scan, m/z range: 30-350). The EI-mass spectra were compared with the NIST library spectra.

2.6. Statistical analysis

Morphophysiological data was subjected to statistical evaluation using one-way analysis of variance (ANOVA), followed by Tukey's honestly significant difference (HSD) *post hoc* test at a significance level of $p \leq 0.05$. Quality attributes, biochemical parameters, and metabolite data were subjected to statistical evaluation using two-way analysis of variance (ANOVA), followed by Tukey's HSD *post hoc* test ($p \leq 0.05$). All statistical analyses were performed using GraphPad Prism version 10.4.1 (GraphPad Software, San Diego, CA, USA).

For VOCs, the original data matrix (VOCs concentration versus treatment) was standardized prior to multivariate analysis to facilitate

the comparison of relative compound abundance. Hierarchical clustering analysis was applied to visualize treatment-related differences in VOC profiles using heatmap representation. Principal component analysis (PCA) and heatmap visualizations were generated with ClustVis 2.0 following the methodology described by Metsalu and Vilo [50], employing Euclidean distance as the clustering metric.

3. Results & discussion

3.1. Environmental conditions and microclimate modifications under AgriPV and white net

The present study was conducted from August to November, 2025, a period characterized by strong seasonal variation in environmental conditions, where temperature and radiation levels change significantly. Monitoring of environmental conditions in this study, confirmed that the installation of AgriPV and white net system as well as the white net alone had a significant impact on canopy microclimate compared to open field cultivation. Even though average air temperature remained relatively stable across treatments, the AgriPV installation reduced incoming solar radiation, offering a more favourable microclimate for raspberry production (Figure 2A–C).

The relative humidity ranged from 61.6, 63.3 to 63.6 in Open Field, White Net, AgriPV & White Net systems, respectively, without significant differences (Fig. 2B). Water for irrigation was then applied with the same amount in the different treatments inducing moisture conservation and lower EC (Figure 2B–D, Supplementary Table 1). Results reported herein are aligned with other studies mentioning similar reduction in radiation under AgriPV, highlighting a stress mitigation under hot and dry conditions [51], while humidity-related responses may vary depending on the system design, local conditions applied and color of net [52,53]. In the current study, the white net alone enhanced plant physiological response compared to open air as it was found for perennial fruit crops as olive [54].

Substrate electrical conductivity and moisture were highly variable among treatments but the maximum values were recorded in Open Field ($939\ \mu\text{S/cm}$), while in AgriPV & White Net and White Net the maximum values were lower: $741\ \mu\text{S/cm}$ and $517\ \mu\text{S/cm}$, respectively (Fig. 2G).

3.2. Physiological responses of raspberry plants under agri-photovoltaic

The system was designed to regulate PAR, improve light uniformity for raspberry growth, and provide protection against hail, and extreme weather conditions. The physiological measurements demonstrated how the incorporation of such systems in the cultivation of raspberries can impact plant responses. Absorbed PAR was higher in open field conditions and the lowest under the AgriPV setup (Fig. 3G), in compliance with the meteorological data and the impact of AgriPV to incoming solar radiation (Fig. 2C). The reduction of solar radiation was reflected in reduced leaf temperature under white net, alone or with AgriPV, during temperature extremes (428 and 449 DAP) (Fig. 3F). Microclimate conditions created under the AgriPV system has likely contributed to the lower VPD leaf observed at 449 DAP, indicating limited water evaporation from leaf surface. Similar findings have been reported in other studies where reduced solar radiation and leaf temperatures are consistent under Agri-photovoltaic and support enhanced physiological responses under stress conditions [51–53].

These modifications of plant microclimate is particularly important to raspberry that is considered relatively tolerant under mild shading conditions [29]. In the current study, the raspberry cultivar showed exceptional phenotypic plasticity even when shading was 70%. The microclimate changes observed in this study were closely linked to stomatal conductance and light utilization. Stomatal conductance was variable along the season and treatments: open field cultivated plants exhibited lower values while AgriPV & White Net alone had higher stomatal conductance early in the season (Fig. 3A). Transpiration

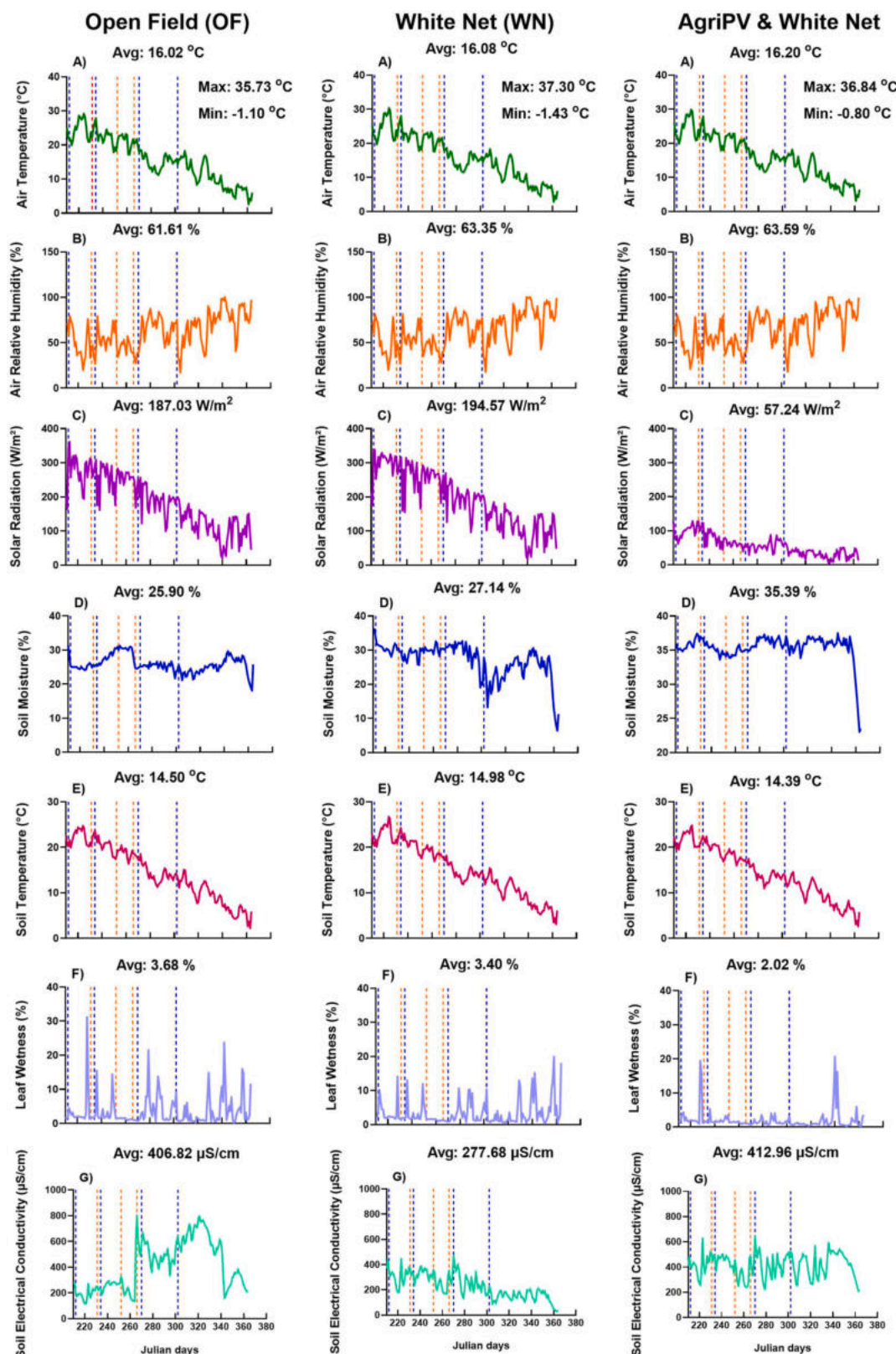


Fig. 2. Changes in (A) air temperature (°C), (B) air relative humidity (%), (C) solar radiation (W m^{-2}), (D) soil moisture (%), (E) soil temperature (°C), (F) leaf wetness (%), and (G) soil electrical conductivity ($\mu\text{S cm}^{-1}$) under different treatments: Open Field (OF), White Net (WN), and AgriPV combined with White Net (AgriPV & WN). Leaf measurements were conducted on four dates: August 1, August 22, September 28, and October 30, corresponding to Julian days 212, 234, 270, and 302 (428, 449, 486, and 518 days after planting [DAP], respectively), indicated by blue dotted lines. Fruit harvest has occurred on three timepoints: August 20, September 10, and September 24, corresponding to Julian days 231, 252, and 266 (447, 468, and 482 DAP, respectively), indicated by red dotted lines.

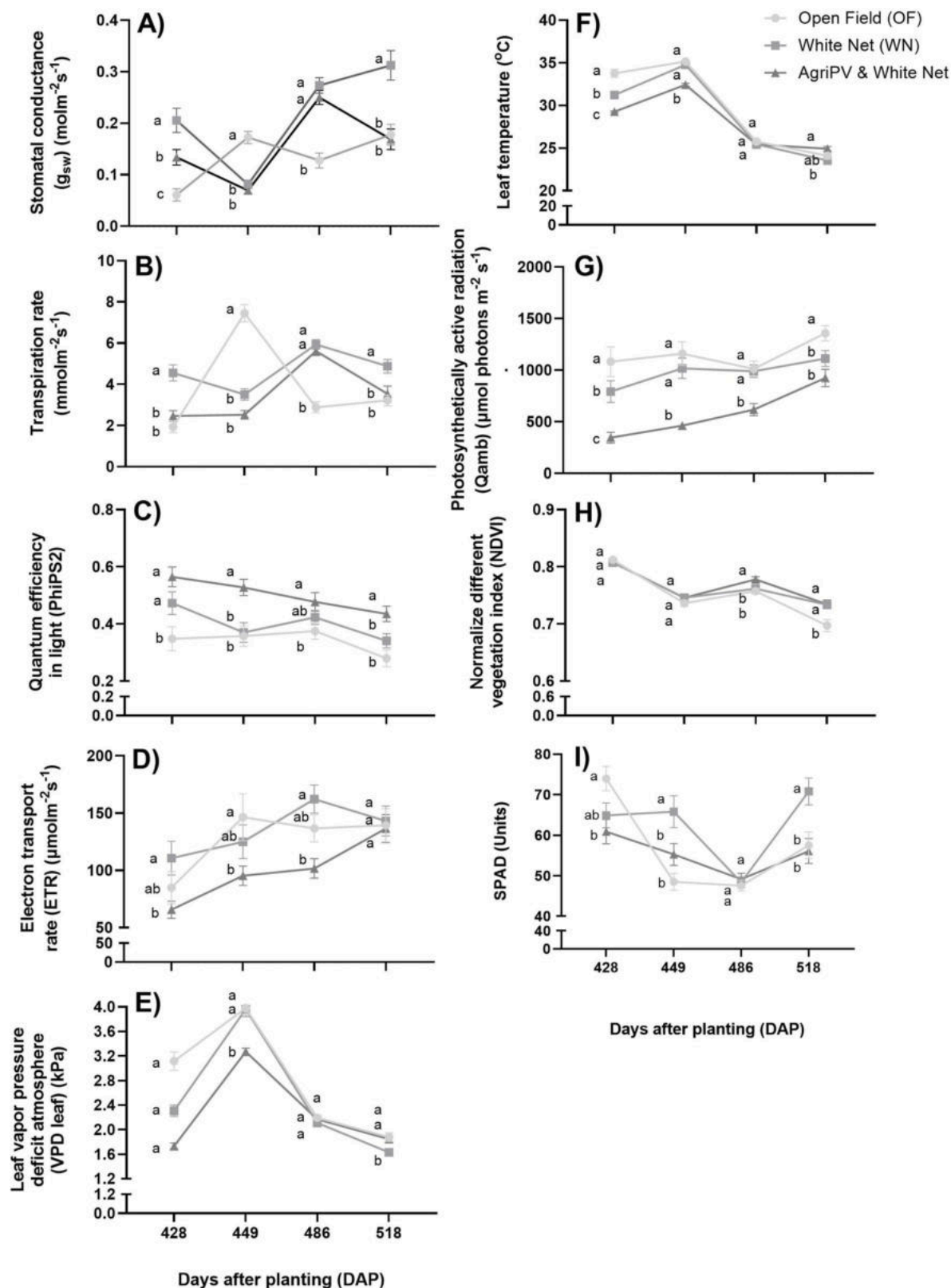


Fig. 3. The effect of different treatments [Open field (OF), White net (WN) and AgriPV & white net (AgriPV & WN)] and different dates (August 01, August 22, September 28 and October 30 corresponding to 428, 449, 486 and 518 DAP, respectively) on A) stomatal conductance (g_{sw}), B) transpiration rate, C) quantum efficiency in light (Φ_{PS2}), D) electron transport rate (ETR), E) Leaf vapor pressure deficit atmosphere (VPD leaf), F) Leaf temperature, G) Photosynthetically active radiation (Qamb), H) Normalized different vegetation index (NDVI) and I) SPAD of raspberry leaves (cv. 'Wengi'). Error bars represent $\pm$ SE. Different letters indicate significant differences ($p \leq 0.05$) within each date.

displayed variability along the season with AgriPV and white net to remain moderate and depicting a stable pattern compared to the open field (Fig. 3B). Quantum efficiency of PSII (Φ PSII) was positively affected under AgriPV, indicating the improved photosynthetic performance observed due to the altered light environment (Fig. 2C). Results from physiological measurements, suggest improved light-use efficiency and a more favorable microclimate due to lower Vapor Pressure Deficit during the summer period as reported for crops grown under limited light conditions using Agri-photovoltaics [52,53].

Overall, the present study demonstrates that incorporation of AgriPV system in raspberry production system can affect its performance through modifications of the canopy microclimate conditions, reducing solar radiation and leaf temperature and thus reducing stress to which plants are subjected, particularly during the summer period.

3.3. Yield performance and water use efficiency under different cultivation systems

Raspberry fruit productivity was positively affected by AgriPV & White Net production system across the harvest period with the greatest benefits observed during temperature extremes (Fig. 4, Table 1). In particular, during August (429-457 DAP), AgriPV/white net treatment had the most significant percentage increase compared to the open field cultivation, increasing the production by 89% and highlighting the strong positive effect of the microclimate modifications that occur due to

AgriPV installation (Table 1). Strong positive effect on yield is also shown by the comparison of AgriPV & white net and white net alone illustrating the synergistic effect when AgriPV were placed above the net (Table 1). During September, the yield remained significant higher under AgriPV while the magnitude of increase was progressively declined from October onwards until the end of the growing season. Specifically, the AgriPV & White Net system achieved cumulative yield

Table 1

Percentage increase in cumulative yield of raspberry plants under agrivoltaic system combined with white net (AgriPV & White Net), White Net (WN) alone, and Open Field (OF) cultivation. Values represent the relative monthly percentage increase in cumulative yield across the harvesting season and correspond to specific days after planting (DAP). Comparisons among cultivation systems are presented accordingly.

Month	DAP	AgriPV&White Net compared to OF	White Net compared to OF	AgriPV& White Net compared to White Net
August	429-457	89%	12%	69%
September	459-487	76%	25%	40%
October	490-518	41%	9%	29%
November	522-539	10%	0%	10%

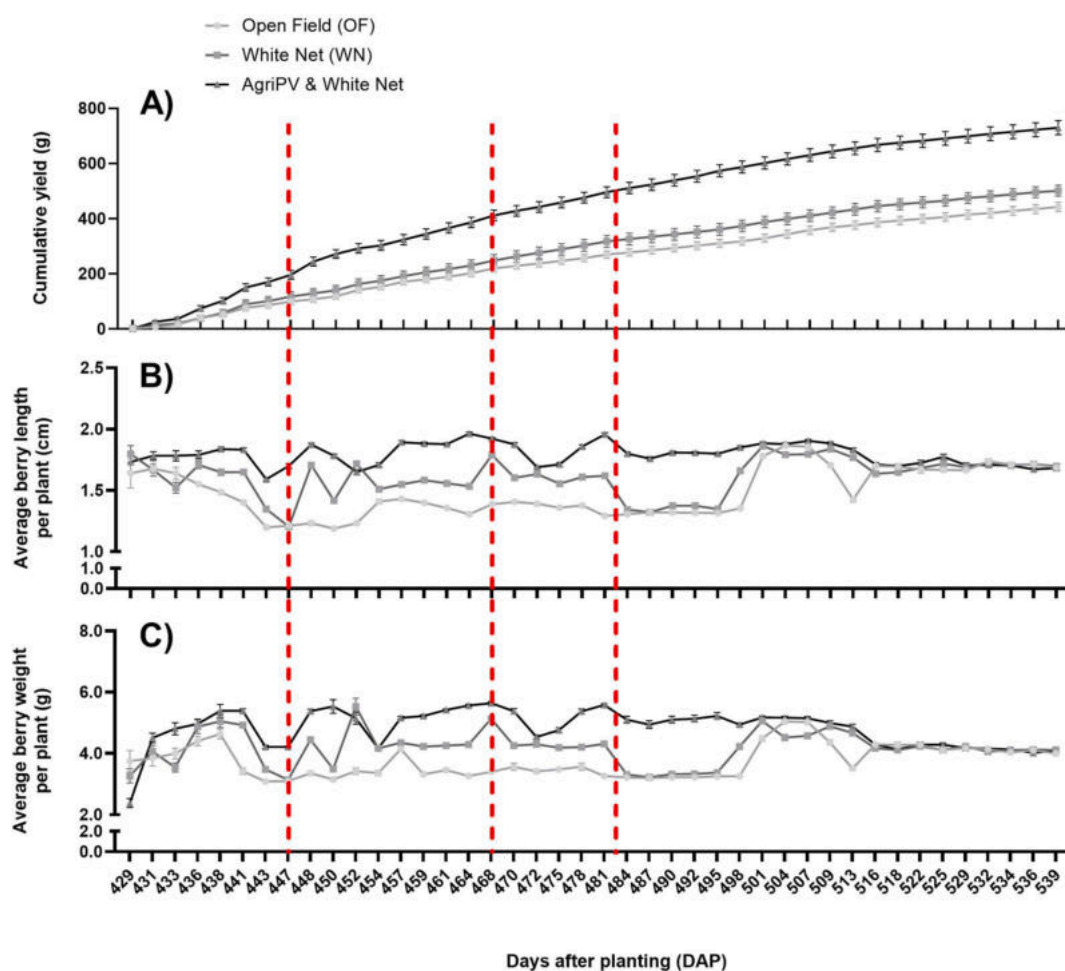


Fig. 4. A) Cumulative yield (g), B) average berry length per plant (cm), C) average berry weight per plant (g) for the forty-two harvests along the growing season (August 02 to November 11 correspond to 429 and 539 DAP, respectively) for different treatments [Open field (OF), White net (WN) and AgriPV & white net (AgriPV&WN)] of harvested raspberry fruits (cv. 'Wengi'). The harvest of the fruits was done at 3 different dates (August 20, September 10 and September 24 corresponding to 447, 468 and 482 DAP, respectively) as shown with red dotted lines. Error bars represent $\pm$ SE.

increases of 89% in August, 76% in September, 41% in October, and 10% in November relative to open field cultivation, with the largest benefits coinciding with peak summer heat stress.

Overall, throughout the whole production season, a substantial yield

increase of 65% under AgriPV & White Net compared to Open Field was monitored. The yield increase was less pronounced (13%) when White Net alone was placed above the plantation. Noteworthy, water use efficiency (WUE) increased under AgriPV & White Net and White Net by

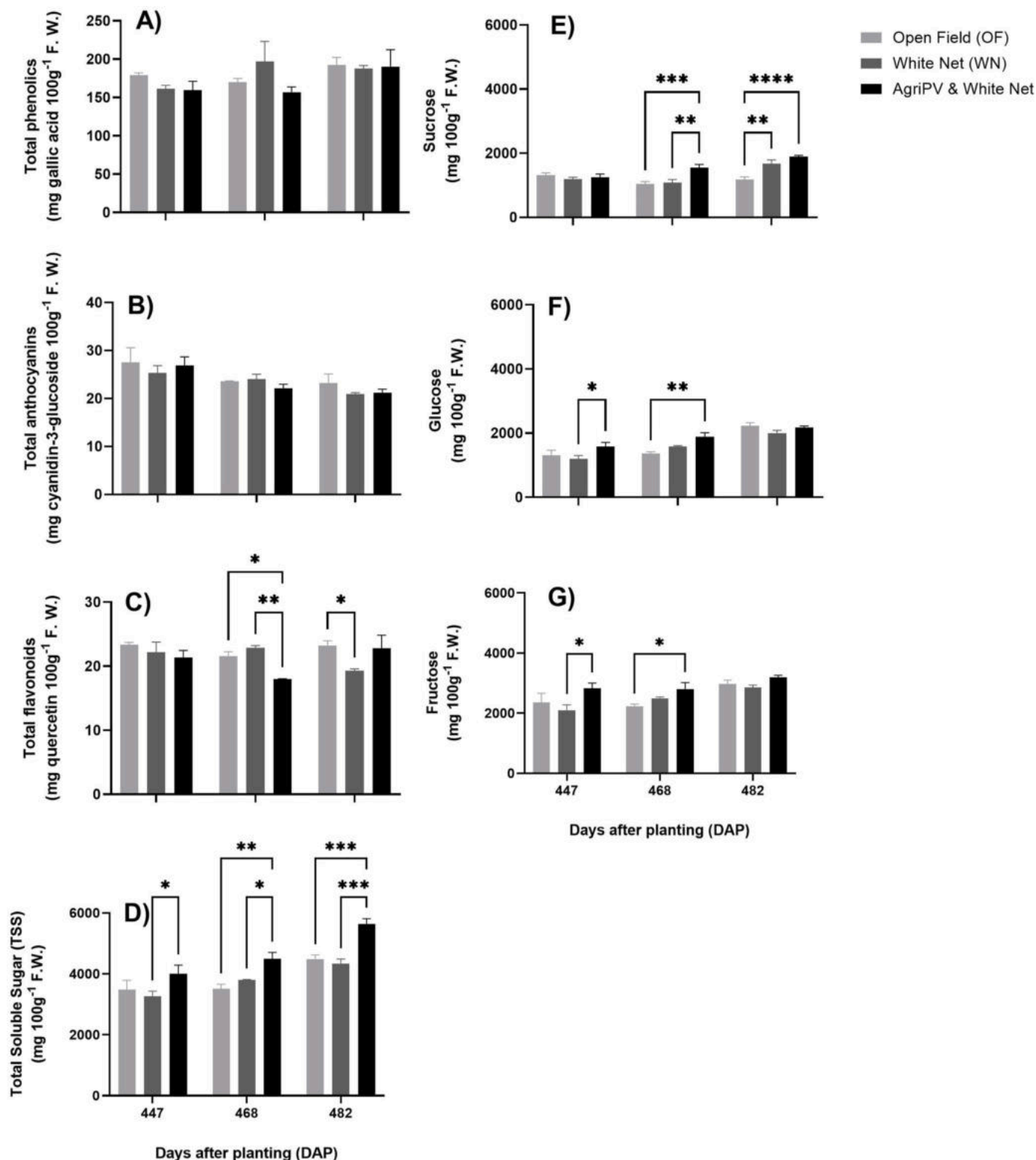


Fig. 5. The effect of different treatments [Open field (OF), White net (WN) and AgriPV & white net (Agri PV & WN)] and different dates (August 20, September 10 and September 24 corresponding to 447, 468 and 482 DAP, respectively) on A) total phenolics, B) total anthocyanins, C) total flavonoids, D) reduced ascorbic acid, E) sucrose, F) glucose, G) fructose of raspberry fruits (cv. 'Wengi'). Values that differ within each date with significance levels (ns = $p > 0.05$, * = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$, **** = $p \leq 0.0001$) are marked with asterisks. Error bars represent $\pm$ SE.

60% and 10% compared to Open Field, respectively. Thus, towards production of 1g yield of red raspberry fruit the water applied was 1.07 and 1.56 L, respectively compared to 1.76 L in Open Field (Supplementary Table 1).

This pattern suggests that the yield benefits due to agrivoltaic systems are more pronounced during periods of high temperatures and radiation. Similar results have been reported in previous studies where yield improvements in response of PV panels mainly occurred during extreme stress events, whereas yield reductions are possible under moderate stress conditions [51,53]. Findings from a recent meta-analysis support the results of the present study, demonstrating that the incorporation of moderate shading into berry production systems grown under high-radiation environments can lead to significant enhancement of the cumulative yield [29].

3.4. Fruit quality attributes

Soluble solids content (SSC, 8.26–10.56 °Brix) varied mainly among the harvesting dates but to a lesser extent among the cultivation systems. Titratable acidity (TA, 1.95–2.48% citric acid equivalents) remained relatively stable among treatments and harvest dates. Lower values of SSC were recorded on the second harvest (468 DAP), while fruits from the latest harvest (482 DAP) were characterized by higher SSC values across all production systems (Supplementary Table 2). Overall, the results indicated that the netting system, alone or in combination with AgriPV, did not negatively influence the sweetness-acidity balance of the fruits.

A significant impact of the treatments was recorded mainly in sugar-related fruit attributes, while secondary metabolites showed limited variation among treatments (Fig. 5A–C). TSS content was generally higher under the AgriPV & White Net treatment at all harvest dates compared with white net alone and open field cultivation (Fig. 5D). A similar pattern was also observed for sucrose content at 468 and 482 DAP: fruits from AgriPV & White Net cultivation exhibited higher sucrose concentrations compared to open field and white net treatments (Fig. 5E). The AgriPV & White Net production system also improved glucose and fructose contents at the early harvests (447 and 468 DAP) compared with the other applied cultivation systems, while no significant changes were observed at the latest harvest for these parameters (Fig. 5F and G). Sugar accumulation under photovoltaic systems was reported to be unaffected in previous studies, indicating that the impact of such treatments may be influenced by different factors, such as environmental conditions and crop characteristics [55].

In contrast to sugar accumulation, no significant effect on total phenolic and total anthocyanin contents under the different production systems was detected. Total flavonoids at 468 and 482 DAP went descending in protected cultivation (white net and AgriPV/white net systems) compared to the open field (Fig. 5A–C). To what extent the changes in the micro-environment of raspberry production (covered *versus* open field cultivation) affects secondary metabolism need to be further explored.

3.5. Polyphenolic compound analysis

LC-MS analysis led to the identification and quantification of 16 polyphenolic compounds in raspberry fruits. The most prevalent compounds in all harvest dates (August 20, September 10, and September 24 in 2025 corresponding to 447, 468 and 482 DAP, respectively) were cyanidin's derivatives. The concentration of cyanidin-3-O-rutinoside, which is one of the key anthocyanins in raspberries, is presented in the highest content in all the samples. Cyanidin belong to anthocyanins, a group of compounds with high antioxidant activity and is typically found in red raspberries both in its free form and as glucoside derivatives [56,57]. Two of the three derivatives of cyanidin that have been found in the raspberry samples have not been affected by the AgriPV & White Net set up, alone or in combination with netting systems (Fig. 6). However, a

noticeable decrease in the concentration of cyanidin-3-O-rutinoside was observed from the 447 DAP to 482 DAP, whereas an increase in cyanidin-3-O-sophoroside (or cyanidin-3,5-diglucoside) was evident.

It appears that most compounds in different harvest dates was not affected by the application of the White Net, alone or in combination with AgriPV, whereas quercetin derivatives showed a significant decrease compared with 'Open Field' fruits. In a previous study, it was reported that the quercetin content in raspberry fruits can vary depending on the environmental conditions [58]. Moreover, data reported herein showed that ellagic acid derivatives mainly went descending during the second (468 DAP) and third (482 DAP) harvest. In raspberry fruits, ellagic acid predominantly occurs bound to larger molecules known as ellagitannins and contribute substantially to its antioxidant capacity [59].

Conversely, catechin that is one of the main non-anthocyanin phenolics in fresh red raspberries [60], showed increased levels at the first harvest (447 DAP) under net, alone or in combination with AgriPV, compared with the 'open field' conditions, while no significant differences were detected at the other harvest dates. In addition, apigenin-7-O-glucoside exhibited an increase during the first harvest date (447 DAP) under the White Net compared with fruits from the Open Field plants, followed by a significant decrease at the third harvest date (482 DAP).

The use of a netting system in fruit tree crop cultivation can significantly influence polyphenol concentrations and subsequently affect the fruit antioxidant properties. Variable responses have been reported in different crop species and netting systems. For instance, in a study on apples cultivated under gray and red nets, higher levels of quercetin and its derivatives were reported, while the concentrations of certain phenolic acids generally declined under these conditions [61]. In contrast, another study on tomatoes found no significant differences in polyphenol concentrations under white nets compared with open field conditions [62]. Blueberries grown under PV panels showed reduction in their antioxidant capacity compared to those grown in open fields [63]. In the present study, quercetin's derivatives level decreased under the White Net and only catechin levels increased significantly. These findings indicate that the effects of netting and AgriPV systems on polyphenol composition are highly dependent on both the fruit species and the type of net and PV panel used.

3.6. Volatile Organic compounds (VOCs) in raspberry fruits

A total of 78 distinct VOCs compounds were identified (Supplementary Table 3 and 4). Among all the analysed samples, the most abundant compounds detected were α -ionone, β -ionone, hexanal, nonanal, 2-butanone, ethanol, acetaldehyde, pentanal, 2-hexenal, ethyl acetate. These compounds were consistently detected across all the samples, highlighting their prominence in the volatile profile of raspberry fruits. The majority of such compounds in raspberries have been also identified in previous studies [64–66].

Volatile compounds are typically associated with aroma perception, contributing to the characteristic flavor and sensory quality of fruits. Since PV panels and protective nets modify the microclimate by altering light availability, temperature, and water conditions, they may indirectly influence raspberry aroma and flavor by mitigating environmental stress [67–69].

Principal Component Analysis (PCA) revealed a clear discrimination of samples harvested at three distinct dates (447, 468, and 482 DAP, respectively), indicating that the harvest time strongly influences the overall VOC profile (Supplementary Fig. 1A). The first two principal components, PC1 and PC2, accounted for 63.2% of the total variance in VOCs, with PC1 summarizing 34.1% and PC2 summarizing 29.1%. The score plot showed distinct clustering of the three harvest points, indicating marked differences in their VOCs profiles. Fruits harvested at 447 DAP were primarily separated along negative PC2 values, whereas 468 DAP samples were associated with positive PC1 and PC2 values. Samples

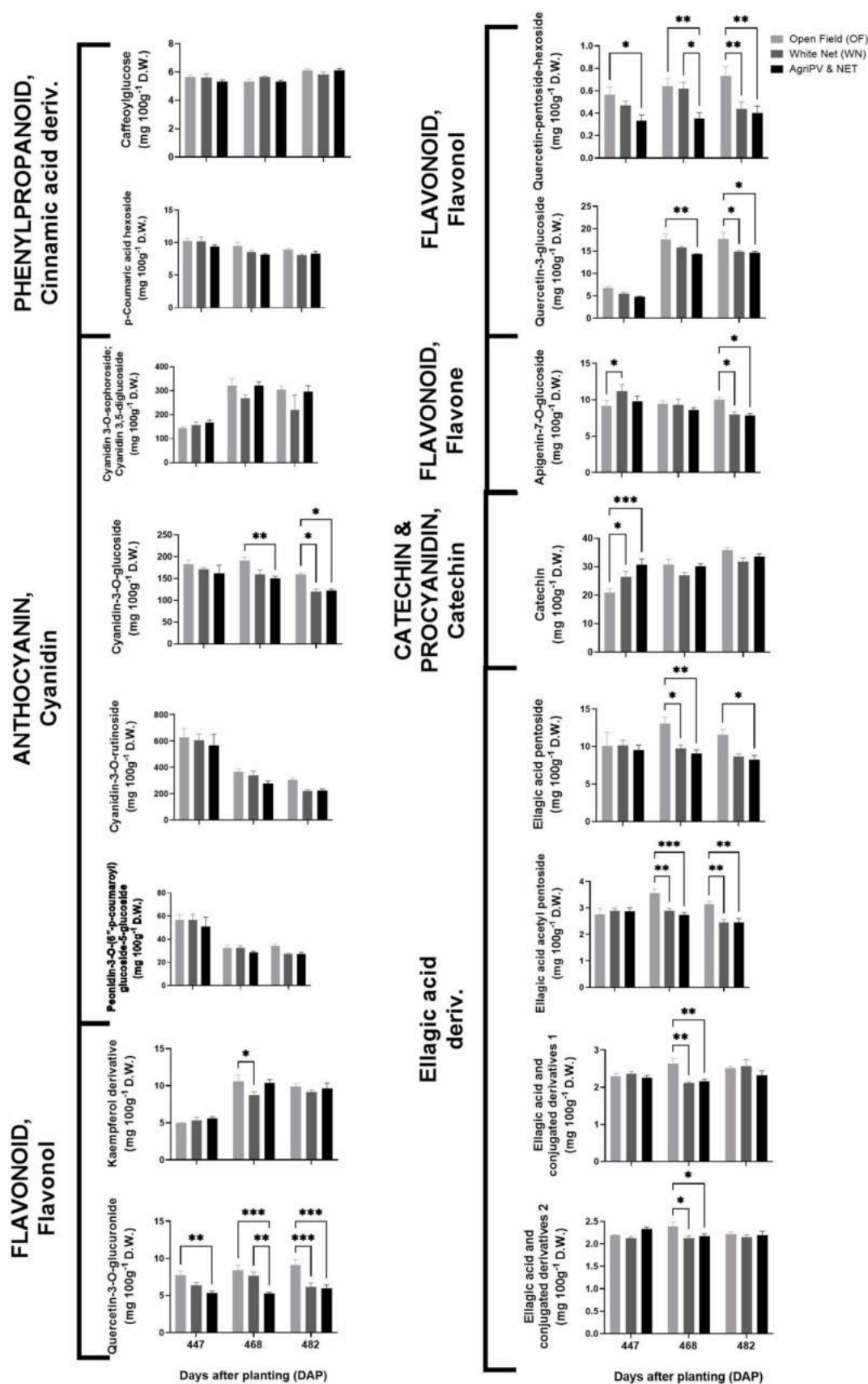


Fig. 6. Content of individual classes (phenylpropanoid, anthocyanin, flavonoid, catechin and procyanidine, organics) of metabolomics data of different treatments [Open field (OF), White Net (WN) and AgriPV & White Net (AgriPV&WN)] and different dates (August 20, September 10 and September 24 corresponding to 447, 468 and 482 DAP, respectively) of raspberry fruits (cv. 'Wengi'). Values that differ within each date with significance levels (ns = $p > 0.05$, * = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$, **** = $p \leq 0.0001$) are marked with asterisks. Error bars represent $\pm$ SE.

collected at 482 DAP were mainly positioned along negative PC1 values.

The corresponding loading plot indicates that separation along PC1 was driven mainly by compounds, such as ethyl acetate, acetic acid and pentanal, loaded positively and were predominantly associated with samples from 468 DAP. In contrast, aldehydes such as hexanal, heptanal, and decanal loaded negatively on PC1 and were associated with samples from 482 DAP. PC2 further differentiated the samples, with compounds such as octanal, nonanal, and 1-octanol contributing positively, while ionones contributed negatively, summarizing the vertical separation observed (Supplementary Fig. 1B).

Overall, the PCA score plot demonstrates good discrimination among the three considered DAPs, suggesting systematic compositional differences and harvest-time-dependent compositional differences in VOC profiles. Notably, this analysis suggests that raspberry VOC composition under White Net, AgriPV & White Net, and Open Field conditions does not differ significantly, as samples cluster primarily according to harvest date rather than the cultivation system.

The heatmap clearly illustrates a developmental shift in the volatile profile across the three harvest dates, indicating that fruit development and harvest stage play a dominant role in the VOCs' composition (Fig. 7). The first harvest date (447 DAP) is characterized by higher levels of aldehydes, such as octanal, nonanal and the terpene, D-limonene, which are associated with floral, fruity, and citrus-like notes

[70–72]. This suggests that fresh, varietal, and citrus-derived aromas dominate at earlier developmental stages. At the second harvest date (468 DAP), an enrichment of C6 and C7 aldehydes and alcohols, such as hexanal and heptanal is observed. These compounds cluster together and are commonly associated with green and grassy sensory attributes [73], reflecting the activation of lipid oxidation pathways [74,75] and indicating a transitional aroma phase. In the third harvest date (482 DAP), the heatmap reveals increased relative abundance of fermentation- and degradation-related compounds, including ethyl acetate, acetic acid, and short-chain ketones, such as 2-pentanone [76–78]. These compounds contribute fruity, vinegary and sweet notes, pointing to advanced ripening or early senescence processes and a shift toward more complex, but less fresh, aroma characteristics [64,79].

These results indicate that VOCs' composition was more affected by the harvest date than by cultivation conditions, indicating a robust, developmentally driven aroma evolution. The observed sensory trajectory, from citrus and floral notes, to green and grassy aromas, and finally to sweeter, fermentation-related volatile compounds, highlights the compound classes most responsible for flavor changes during raspberry fruit development.

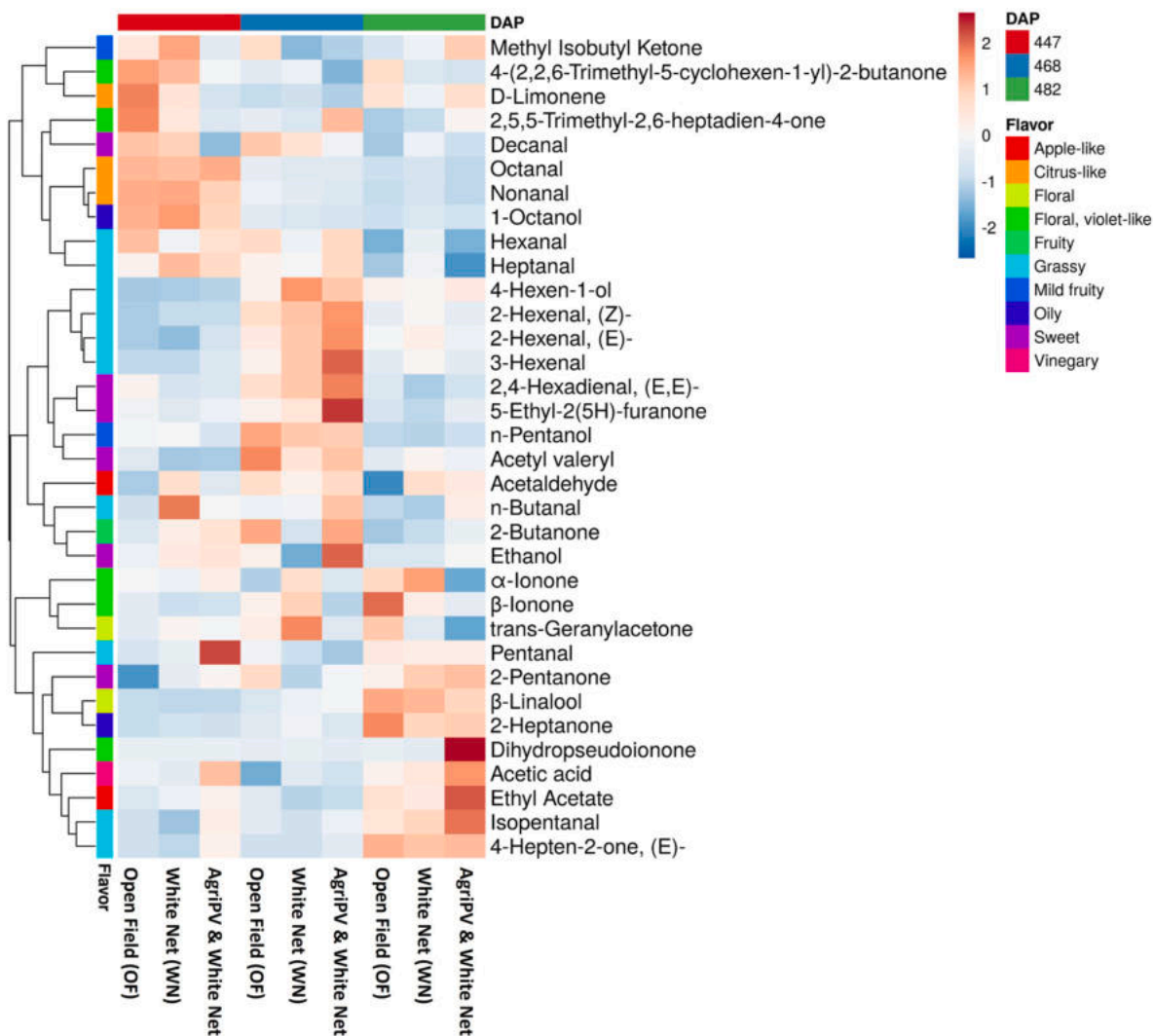


Fig. 7. Heatmap representing the fold changes of VOCs data of different treatments [Open field (OF), White net (WN) and AgriPV & white net (AgriPV&WN)] and different dates (August 20, September 10 and September 24 corresponding to 447, 468 and 482 DAP, respectively) of raspberry fruits (cv. 'Wengi'). The data were standardized as described in Section 2.6 Statistical analysis.

4. Conclusions

The semi-transparent PV modules combined with the tailored netting system effectively reduced canopy temperature and increased relative humidity, thereby mitigating heat stress during the summer months that temperature extreme episodes may occur, and improving the microclimate conditions. Physiological measurements showed enhanced photosynthetic performance of raspberries under PV-induced shading compared with sunlight fully exposed plants, indicating that moderate, spectrally filtered shade can better align light availability with the species' photosynthetic capacity. This enhanced plant behaviour was translated into increased fruit production under the AgriPV cover, while fruit quality attributes such as soluble solids and titratable acidity exhibited measurement-date-dependent responses, highlighting the dynamic interaction between shading intensity, ripening stage, and environmental conditions.

The installation and first-year operation of the semi-transparent AgriPV system demonstrated that a dual land use for raspberry production and electricity generation is both technically feasible and agronomically beneficial under Mediterranean conditions. Overall, the pilot confirms that carefully designed AgriPV systems, combining optimized transparency, structural layout, and adaptive netting, can enhance resilience and productivity in high-value crops while contributing to renewable energy targets. Results reported herein support the suitability of raspberries, and potentially other soft fruits, as candidate crops for integration under AgriPV structures, particularly in areas that suffers from temperature extremes during the summer period. Future studies should additionally assess the energy perspective (PV yields) from these set ups and extend the monitoring period across multiple seasons, refine species- and cultivar-specific shading prescriptions, and incorporate detailed techno-economic and life-cycle assessments to guide commercial-scale deployment.

CRedit authorship contribution statement

Egli C. Georgiadou: Data curation, Formal analysis, Investigation, Methodology, Supervision, Visualization, Writing – original draft. **Nicolas Valanides:** Investigation, Methodology, Project administration, Writing – review & editing. **Eleni D. Myrtesi:** Data curation, Formal analysis, Methodology, Writing – original draft. **Maria Parcharidou:** Investigation, Methodology, Writing – original draft. **Anna Maria Taliadorou:** Methodology, Writing – review & editing. **Andreas Livera:** Writing – original draft, Writing – review & editing. **Sofia Torrado:** Investigation, Methodology. **Rocio García-Villalba:** Data curation, Formal analysis, Methodology. **Samuele Crescenzi:** Investigation, Methodology. **Enrico Maria Lodolini:** Conceptualization, Writing – review & editing. **Francisco Tomás-Barberán:** Data curation, Formal analysis, Writing – review & editing. **Davide Neri:** Conceptualization, Data curation, Writing – review & editing. **George A. Manganaris:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jafr.2026.103128>.

Data availability

Data will be made available on request.

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