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Agrivoltaics for Ornamental Plant Nurseries: Innovation to Enhance Crop Protection and Energy Production

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Abstract. Nursery crops, especially potted ornamental plants, are increasingly vulnerable to climate extremes, notably root damage from high substrate temperatures. Dynamic agrivoltaic systems (DAV) offer a promising solution by improving microclimate conditions while generating solar energy. Over two contrasting years, six ornamental species were grown near Lyon, France, under three treatments: open-field control with black ground cover (CTL), DAV with black ground cover (DAV-B), and DAV with white ground cover (DAV-W). DAV reduced incident radiation by up to 43%, lowered air and leaf temperatures (up to -15°C), and increased relative humidity, limiting plant stress. Substrate temperatures decreased by up to 8°C, with DAV-B significantly improving root development in 2024. Species responses varied: for instance, *Lagerstroemia indica* showed enhanced canopy diameter under DAV, while *Photinia x fraseri* declined slightly. The white ground cover increased reflected PAR, further reduced substrate temperature, and improved both root development and energy production (+6%). These results highlight the potential of DAV systems, especially when combined with nursery-specific innovations, to improve crop resilience and dual land use in ornamental plant nurseries.

Keywords: Ornamental Plants, Microclimate, Root Protection, Energy Production

1. Introduction

Nurseries growing potted plants increasingly face environmental challenges such as prolonged heatwaves, intense solar radiation, and irregular precipitation. This exacerbates the already high irrigation requirements of container-grown plants [1]. Among these challenges, thermal damage to roots stands out as a major limiting factor in plant development and survival. Because the substrate in pots is more exposed and retains less thermal inertia than open-field soil, root temperatures can rapidly rise to harmful levels, especially in small containers [2]. It is well established that root growth begins to slow significantly above 35°C [3], with irreversible damage typically occurring once temperatures exceed 39°C [4]. One promising solution is the use of dynamic agrivoltaic (DAV) systems, which combine dynamic photovoltaic panels with agricultural production and offer real-time adaptability to optimize both plant needs and energy generation. These systems can modulate shading, thus playing a role in regulating the microclimate around the plants [5] with proven climate protection benefits, particularly for trees cultivated in open-field environments [6]. However, the specific impacts of DAV systems on potted ornamental plants remain poorly documented, especially under real nursery conditions. To better understand these interactions, a two-year experimental trial was conducted near Lyon, France, involving six typical ornamental plant species cultivated under a DAV system. This research was carried out in collaboration with several key partners, including CNR, Astredhor, Sun'Agri, CEA, and Campus AgriLyon Vert. Beyond the DAV panels themselves, the system integrated complementary cultivation innovations such as anti-hail nets and reflective white ground covers, aiming to further enhance plant protection, light distribution, and energy production. This study investigates the integrated benefits of DAV systems, not only as a tool to mitigate microclimate but also as a potential contributor to sustainable nursery practices. By comparing growth, agronomical responses, and energy production under DAV versus conventional conditions, we aim to assess the feasibility of this approach for potted ornamental plant production.

2. Material & Methods

2.1 Study site and experimental set-up

The research site is located in Dardilly, France (45°48'42.5"N 4°46'0.6"E). The dynamic agrivoltaic (DAV) system was established at the end of 2022 on an area of 780 m^2 with dynamic panels mounted on 1-axis trackers. Each row of panels is spaced 4.5 m apart and located approximately 4.5 m above the ground. The DAV system consists of seven rows of trackers, each composed of bifacial monocrystalline photovoltaic panels (DM450M6-B72HSW, DMEGC Solar, China) oriented in the north-south direction for a total installed power of 150 kWp. The ground coverage ratio (GCR) of the DAV system is 46%. Trackers are electrically controlled and can be tilted by +/- 85° from east to west. Panel movements were governed by a phenology-driven steering policy protected by patents [7], implemented via Sun'Agri© algorithms and crop model [8]. This policy consistently prioritized crop's needs in terms of irradiation and protection, a strategy designed annually to ensure economic viability by balancing energy generation with agricultural yield. This policy enabled dynamic shading based on real-time environmental data (temperature, radiation) during summer, supplemented by protective movements for rain and wind. This precise protocol, defining specific panel angles and activation rules at each instant. These data are collected and ensure the replicability of the achieved microenvironmental conditions.

This study was carried out in 2023-2024 and six potted ornamental plant species were tested: *Photinia x fraseri* (Photinia), *Elaeagnus ebbingei* (Eleagnus), *Lavandula angustifolia* (Lavandula), *Choisya ternata* (Choisya), *Carpinus betulus* (Carpinus), and *Lagerstroemia indica* (Lagerstroemia). The DAV section had two treatments (Figure 1): one with white ground cover (DAV-W) to study its impact on both electricity and plant production, and another with typical black ground cover (DAV-B) (100% polypropylene, 125 g/m²). In 2023, in addition to being tested on DAV-B and CTL, species of Eleagnus and Photinia were also tested on DAV-W, while in 2024, species of Lavandula and Photinia were tested on DAV-W. An anti-hail net (white high-density polyethylene, shading ratio: 9%) was installed on the DAV structure and deployed from July to October 2023 and not deployed in 2024. These treatments were compared to a control with black ground cover without panels (CTL, 1,150 m²). Irrigation was provided by sprinklers for 3-liters-pots and drip irrigation for 7.5-litre pots. Irrigation was differentially managed between DAV and CTL treatments, based on the crop manager's expert evaluation of plant physiological status and tensiometers (Watermark 6440, Davis Instruments, CA, USA) at a depth of 10 cm in DAV and CTL treatments.

Figure 1. *Aerial view of the different treatments in the agrivoltaic setup with control (CTL), agrivoltaic system with black ground cover (DAV-B) and white ground cover (DAV-W) (left) and photography of potted plants within the agrivoltaic system (right)*

2.2 Energy production

For the electricity part, two of the eleven strings of modules were equipped with monofacialized panels (same bifacial modules with a black opaque film applied on the rear face) to evaluate bifacial gain. Module front side and backside irradiances (IngenieurBüro monocrystalline reference cells), module temperatures (TC Direct planar Pt100 probes) and module inclinations (ASM PTM27 inclinometers) were monitored. The PV string is connected to two inverters and electrical data (voltage, current, power) are also recorded every five minutes. The DAV system offered the possibility to compare bifacial modules over the white cover, bifacial modules over the black cover and monofacial modules over the black cover.

2.3 Weather and microclimate

Weather data (wind direction and speed, air temperature, horizontal solar radiation, relative humidity, and precipitation) was continuously collected using a weather station (6820OV, Davis Instruments, CA, USA) located close to the DAV to measure the outdoor climate and control the solar panels. The micro-environment was measured using a mast equipped with sensors in each treatment: an anemometer and a thermo-hygrometer (6410, Davis Instruments, CA, USA), and a quantum sensor (SQ202XSS, Apogee instruments, UT, USA). Substrate temperature was monitored using two sensors (6477, Davis Instruments, CA, USA) placed at 10 cm depth in pots from each treatment, while leaf temperature was recorded with two sensors (LAT-B3, Ecomatik, Germany) on plants in DAV-B and CTL. On a clear day in July 2024, reflected PAR was measured under DAV at 30 cm and 150 cm above black and white ground covers using a ceptometer (MQ303 Apogee).

2.4 Agronomic parameters

Each experimental season started in mid-May after initial greenhouse growth. Three assessment campaigns were conducted annually in 2023 and 2024: an initial evaluation at the end of the greenhouse phase to characterize the starting conditions of the experiment (t0:2023-06-19 and 2024-05-28), an intermediate measurement during the growing period (t1:2023-09-04 and 2024-07-25) and a final assessment prior to the commercialization of the plants (t2: 2023-10-12 and 2024-09-04). During each measurement campaign, a sample of 30 plants per species and per treatment was assessed when the quantity of plants allowed it. The following parameters were recorded: plant height, two perpendicular canopy diameters, presence of leaf burn symptoms (0 = absent, 1 = present), and root system development, scored on a scale from 0 (very few roots) to 2 (well-developed root system).

3. Results and discussion

3.1 Seasonal weather conditions

The 2023 season in the Lyon region was hot and dry, with 245 mm of rainfall and 2.206 h of sunshine (+8% vs. 1991–2020 average in the region [9]), while 2024 was cooler and wetter, with 964 mm of rainfall and only 1871 h of sunshine (-9% vs. 1991–2020 average in the region [9]). Despite similar summer peaks (37 °C), late-season temperatures were lower in 2024. These contrasting conditions provided a robust framework to assess DAV performance.

3.2 Microclimate modulation by DAV systems

In 2023, cumulative daily incident radiation was reduced by 43% under DAV-B and by 33% in 2024 because the hail net (with a shading rate of 9%) was not deployed that season. As in previous studies on apple trees [5] and raspberries [10] under the same agrivoltaic system, distinct alternating light and shade bands were observed within the plot. East–west transect measurements at 130 cm height with upward-facing PAR sensors in July 2024 revealed a distinct alternation of shaded and sunlit zones within the parcel with incident PAR ranged dramatically from 130 $\mu mol \cdot m^{-2} \cdot s^{-1}$ in shaded areas to 1.700 $\mu mol \cdot m^{-2} \cdot s^{-1}$ in full sun around midday, highlighting the spatial variability generated by the panels.

This reduction in incident radiation under the DAV structure contributed to the formation of a less stressful microclimate. On average, daytime air temperatures under DAV-B were 0.1-0.4°C lower than in the open field, reaching -2°C in August 2024. At night, temperatures averaged 0.1°C higher than the CTL. Relative humidity increased under the DAV structure by 1.4-2.2% during the day and up to +9% in August, with smaller differences at night. Wind speed was significantly reduced under DAV, especially during strong wind events, following an affine function (slope -0.35 $m \cdot s^{-1}$); e.g., a 10 $m \cdot s^{-1}$ wind at the control site dropped to 6.5 $m \cdot s^{-1}$ under DAV. This reduction may limit pot displacement and damage (e.g. broken branches, plant stress), thus lowering labour costs for repositioning and repair in nurseries.

In summer 2023, a notably hot and dry year, DAV-B recorded 17 days with substrate temperatures above 35°C, compared to 43 days for CTL (Figure 2). In 2024, DAV-B had 0 days above 35°C, while CTL experienced 9 such days. By reducing substrate temperatures in the pot, the DAV-B treatment mitigates heat stress on root systems, thereby preventing growth inhibition and damage caused by high temperatures during hot summer periods [4].

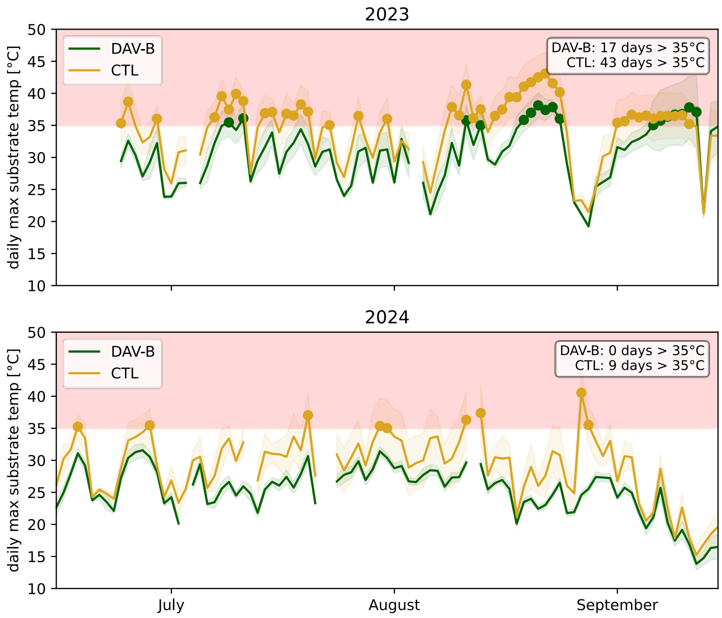

Figure 2. *Daily max substrate temperature [°C] for the agrivoltaic treatment (DAV-B) and control (CTL) with black ground cover during summer 2023 and 2024. The red area represents temperatures above 35 °C; days exceeding this threshold are marked with a dot, and the seasonal count is shown in the top right corner.*

3.3 Impacts of DAV systems on plant development

This temperature buffering effect may partly explain differences observed in root development. Root development, rated from 0 (no roots) to 2 (well-developed roots), did not differ significantly between DAV-B and CTL in 2023 across 3 L and 7.5 L pots (mean scores 0.91 to 1.00; $p > 0.05$). In 2024, however, DAV-B significantly enhanced root growth in both pot sizes (3 L: 1.05 vs. 0.92, $p = 0.041$; 7.5 L: 1.14 vs. 0.99, $p = 0.031$) (Figure 3). This effect may be linked to lower substrate temperatures under DAV-B, as elevated root-zone temperatures in containers impair root growth and water–nutrient uptake, while cooling strategies can significantly mitigate these negative effects [3].

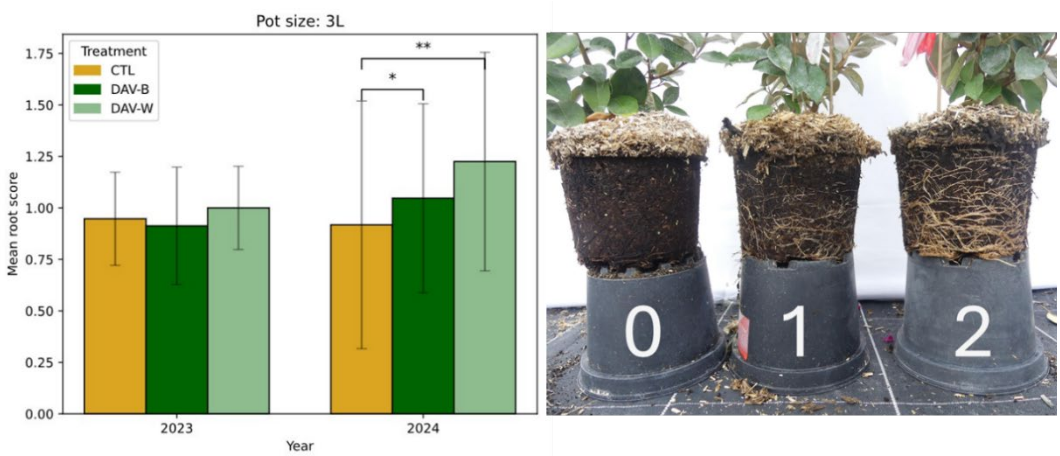

Figure 3. *Mean root development score at final assessment (illustrative qualitative scale shown on the right) across both seasons, all species, and the three treatments (CTL, DAV-B, and DAV-W) for plants grown in 3-litre pots.*

Leaf temperature was significantly reduced by shading under the DAV-B treatment, with average daytime decreases ranging from 0.5°C to 3.5°C depending on the month, and transient drops up to 14.8°C due to moving shade bands. Nighttime differences were smaller. Consequently, leaves in DAV-B experienced substantially fewer hours with temperatures exceeding 35°C. In 2023 (early July to mid-August), the cumulative duration of leaf temperatures above 35°C was 75 hours in DAV-B versus 144 hours in CTL, representing a 48% reduction. In 2024 (early August to mid-September), exposure time above 35°C reached 205 hours in DAV-B compared to 560 hours in CTL, a 63% reduction. These results demonstrate the DAV system's effectiveness in limiting high-temperature exposure and reducing the risk of sunburn and heat-related physiological stress. Leaf thermal tolerance thresholds vary widely among species, typically ranging from 35 to 55°C, and are strongly influenced by exposure duration; even brief exposures to supra-optimal temperatures can cause irreversible damage to photosynthetic tissues [11]. These results highlight the agronomic potential of the DAV system in protecting crops from temperature-induced physiological damage during increasingly frequent summer heat events.

In 2023, a divergence in plant reactions was observed between species. Three species that are traditionally employed in the creation of hedges and growing well in sunny conditions (Carpinus, Photinia and Eleagnus) have been observed to undergo a reduction in height when subjected to the effects of DAV-B. Conversely, DAV-B has been demonstrated to exert a favourable influence on the height of Choisya plants, a species that exhibits a greater degree of shade tolerance. The plant height was reduced by 25%, 19% and 17% respectively for Carpinus and Photinia in 3-litre pots and Eleagnus in 7.5-litre pots, while for Choisya it was increased by 34%.

In 2024, the effect of DAV-B treatment continued to vary by species, with contrasting impacts on growth parameters. No significant difference in height was found for Photinia, Lavandula, Choisya, Carpinus, Lagerstroemia, and Eleagnus in 3L containers (a negative effect of DAV-B was observed in 7.5L) (Table 1). Regarding average canopy diameter, a negative impact of DAV-B was observed for Photinia 3L, Eleagnus 7.5L and Carpinus. Conversely, a positive effect of DAV-B was found for Lagerstroemia and Choisya. Notably, Lagerstroemia exhibited a significant positive response with canopy diameter increasing by 23% compared to CTL (Table 1), reflecting altered plant morphology characterized by a more pendulous growth habit under shading conditions. Photinia responded negatively to DAV-B with a slightly reduced canopy diameter compared to CTL (-11%) in 3-litre pots (Table 1). These findings reinforce that DAV's impact on plant morphology and health is species-specific, highlighting the need to adapt steering policies according to groups of species with similar responses.

***Table 1.** Height [cm] and mean diameter [cm] of the canopy for the six species and the three treatments at the last measurement session in 2024.*

Species	Pot [L]	Treatment	Height [cm]	Mean diameter [cm]
Photinia	3	DAV-B	60.6 ± 8.9 a	42.9 ± 6.2 b
		DAV-W	60.9 ± 12.5 a	42.7 ± 6.5 b
		CTL	57.7 ± 12.0 a	48.3 ± 6.4 a
	7.5	DAV-B	80.3 ± 15.3 a	54.0 ± 7.4 a
		CTL	80.3 ± 15.4 a	57.2 ± 11.6 a
Eleagnus	3	DAV-B	62.5 ± 10.1 a	41.0 ± 5.5 a
		CTL	62.4 ± 11.7 a	42.4 ± 6.1 a
	7.5	DAV-B	83.7 ± 12.3 b	55.3 ± 6.5 b
		CTL	97.2 ± 12.3 a	65.5 ± 5.9 a
Lavandula	3	DAV-B	30.2 ± 4.8 b	19.4 ± 3.4 a
		DAV-W	37.5 ± 2.6 a	22.0 ± 3.7 a
		CTL	34.0 ± 0.0 ab	16.0 ± 0.0 a
Choisya	7.5	DAV-B	59.1 ± 7.2 a	64.5 ± 10.7 a
		CTL	56.1 ± 8.4 a	56.1 ± 11.6 b
Carpinus	3	DAV-B	55.5 ± 15.1 a	41.7 ± 7.6 b
		CTL	58.4 ± 11.8 a	49.8 ± 7.5 a
Lagerstroemia	3	DAV-B	60.9 ± 9.1 a	61.1 ± 7.9 a
		CTL	61.8 ± 7.8 a	49.5 ± 6.0 b

Across contrasting years, DAV consistently modulated microclimate, yet its impact on plant development showed species-specific and inter-annual variations. Root development was significantly enhanced in 2024, but not in 2023. Vegetative growth responses varied: Choisya consistently responded positively or neutrally, while Carpinus, Photinia, and Elaeagnus generally showed negative or neutral impacts across both years. This highlights the intrinsic species-dependency of DAV's effects, necessitating adaptive steering policies.

3.4 Added value of reflective white ground cover

The agrivoltaic system allowed us to evaluate various nursery-specific innovations, including the use of white ground covers and white anti-hail nets, and their combined effects on microclimate, potted-plant development, and electricity production. From a microclimatic standpoint, no significant difference in total incident radiation was observed between the black and white ground covers under the DAV system. However, the white cover markedly increased reflected photosynthetically active radiation (PAR), particularly at solar noon, with average gains of +340 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at 30 cm above the surface (representing up to 48% of incident PAR, compared to 16% for the black cover) and +210 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at 130 cm during a sunny day of July 2024. While air temperature remained comparable between the two treatments during the 2024 season, in 2023, within the DAV system, a slight cooling effect of approximately 0.3°C was observed above the white ground cover compared to the black one. The white ground cover consistently decreased daytime relative humidity by approximately 1.5%. Most importantly, it contributed to substantial substrate cooling: substrate temperatures were on average 3°C lower than those measured above the black cover, with differences reaching down to 8°C during hot summer periods in September 2023. This cooling effect is particularly relevant in potted nursery production, where root zone overheating is a critical constraint. The beneficial effect of the white ground cover under the agrivoltaic system on root development is reflected in the end-of-season root scores, with averages of 0.91 and 1.04 for DAV-B compared to 1.00 and 1.22 for DAV-W in 2023 and 2024, respectively (Figure 3). These microclimatic modifications translated into tangible benefits for plant growth also. In 2023, DAV-W had an enhancing effect on canopy diameter for Eleagnus and Photinia in 3-litre containers, compared to DAV-B. In

2024, the use of a white ground cover in the DAV-W treatment led to a 24% increase in Lavandula height compared to the standard DAV configuration with black ground cover (Table 1). While the white ground cover undeniably contributed to increased PAR reflection, potentially enhancing photosynthesis in the lower canopy, and a minor air-cooling effect, the primary contribution to improved root development appears to stem from the substantial reduction in substrate temperature. This cumulative dual effect, where the alleviation of root thermal stress, a well well-established factor inhibiting root development, seems predominant, effectively explains the observed benefits.

3.5 Energy production and technical innovations

Finally, the agrivoltaic structure also provided insights into how these innovations affect electricity production under dynamic steering policies. While agronomic steering policies such as anti-tracking led to energy losses: typically, 25-30% on partial anti-tracking days and between 26-55% on full anti-tracking days, specific innovations helped mitigate these losses. First, the use of bifacial photovoltaic modules provided a clear advantage, with averaged gain in energy produced of approximately 13% compared to monofacial modules, both types placed over a black ground cover, thanks to their ability to harness reflected radiation. Secondly, the deployment of white anti-hail nets, which are particularly valuable for protecting young nursery plants highly vulnerable to hail damage, improved rear-side irradiation by about 15%, independently of the ground cover colour. Lastly, the white ground cover itself contributed an additional 6% gain in electricity production via albedo enhancement, as shown by comparing two bifacial strings, one above a black surface and the other above a white one. These combined innovations illustrate how agrivoltaic systems can be optimized to maximise energy performance while prioritizing crop needs.

4. Conclusion

This study highlights the potential of dynamic agrivoltaic systems (DAV) to improve microclimatic conditions in container-grown nursery crops, notably by reducing leaf and substrate temperatures. For several species, these thermal buffers led to improved growth for both years and root development in 2024. Despite the unusually low solar radiation that year, no detrimental effects were observed under DAV, highlighting the system's resilience and adaptability. According to results obtained in 2023 as in 2024, species responses varied, reinforcing the need for targeted steering policies based on physiological groupings rather than average steering policy. While crop-oriented steering policies can reduce energy yield, technical solutions such as bifacial PV panels, reflective ground covers, and anti-hail nets helped mitigate energy losses. Future research should focus on optimizing steering policies for physiologically similar plant groups to fully exploit the agronomic and energetic benefits of agrivoltaism in nursery systems. These findings are highly relevant for all young plantations, highly vulnerable to climatic extremes due to limited root systems. DAV systems offer a robust solution for root thermal stress, high irrigation demands, and limiting leaf burn. Integrating technical innovations like anti-hail nets exemplifies how dual-benefit tools enhance electricity production while directly aiding plant protection. Such integrated designs for agrivoltaic projects maximize both agricultural resilience and energetic efficiency.

Data availability statement

The data that has been used is confidential.

Author contributions

CT, JD, JN, HC and PJ: Investigation. PJ, JD, HC: Formal analysis. PJ, JD and HC: Writing – original draft. DF, CC and XB: Conceptualization, Supervision and Project administration.

Competing interests

The authors declare that they have no competing interests.

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