

Photovoltaic modules performance and carbon footprint assessment in agrivoltaic system

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ABSTRACT

We ran a two-month field trial (1 August – 30 September 2025) on a farm near Baghdad to see how lifting PV modules over a crop changes their electrical output, their operational carbon intensity, and the yield of the tomato (*Solanum lycopersicum* L.) grown underneath. Monocrystalline and polycrystalline modules were each installed in two ways: close to the ground over bare soil (C-PV) and on a 2 m agrivoltaic frame (AV). In total, 720 observations of I–V curves, module temperature, irradiance and energy yield were collected. The AV modules averaged 63.5 °C and the ground-mounted ones 76.3 °C. That 12.8 °C difference is two to four times the 3–7 °C usually quoted for temperate installations, which suggests elevation pays off most where the heat load is highest. In the two-way ANOVA, both mounting and module type affected efficiency, power gain, energy, carbon intensity and temperature ($p < 0.001$ for most terms). Efficiency went from 11.25% on C-PV to 15.39% on AV; monocrystalline modules gained more (11.26% → 16.45%) than polycrystalline ones (11.24% → 14.32%). Carbon intensity fell by 29.9% on the AV frame (70.26 → 49.23 g CO₂e kWh⁻¹). Since we used fixed emission factors for each technology, this drop reflects only the larger amount of energy delivered per unit of embodied emission. Tomatoes under the panels yielded 3.452 kg m⁻², against 3.635 kg m⁻² in the open-field control (C-Ag); one-way ANOVA ($n = 144$) gave $p = 0.053$, i.e. not significant, though only just. The results are set against recent agrivoltaic, land-use and life-cycle studies. Over one season, the raised frame gave more electricity with no measurable yield cost, and the layout deserves wider testing in hot-arid parts of Iraq and central Türkiye.

Keywords: agrivoltaics; PV module cooling; monocrystalline vs polycrystalline silicon; carbon intensity; tomato; Baghdad.

INTRODUCTION

Electricity demand in Iraq is climbing at the same time as summers get hotter and irrigation water gets harder to secure, yet farms are still expected to keep producing (Salman et al., 2020). Baghdad is a good example of the squeeze: there is plenty of sunshine, but in July and August module temperatures climb so high that a large share of the possible PV output is lost (Younis et al., 2021). Climate change is also shifting water availability and crop water requirements across the country, which leaves irrigated farming more

exposed and makes systems that save both land and water more attractive (World Bank, 2022).

Agrivoltaics, in which crops and PV modules share the same plot, is one response to these linked pressures. Using one parcel for two purposes eases competition for land, and the panels may also save water, soften the microclimate, and give the farmer a second income (Weselek et al., 2019; Chopdar et al., 2024). In dry and semi-arid areas the shade cast by the structure lowers soil evaporation and leaf heat load and keeps the soil moist for longer, which matters most for crops grown under strong summer sun

(Hassanpour Adeg et al., 2018; Barron-Gafford et al., 2019). For hot-arid zones such as central Iraq and central Türkiye, where water-use efficiency often counts as much as total yield, these effects are directly relevant.

Recent agrivoltaic research has shifted from basic feasibility toward system optimisation and trade-off analysis. Newer studies emphasise that agrivoltaic benefits depend on panel height, spacing, tilt, crop type, and local climatic conditions, because the balance between shading and light availability determines whether yield is protected or reduced (Chopdar et al., 2024). Modelling and field evidence also suggest that the design of the agrivoltaic array can meaningfully reduce crop water consumption while preserving energy production, making the layout of the system a critical determinant of both agronomic and electrical performance (Warmann et al., 2024). Comprehensive simulation-based reviews further show that model-assisted optimisation of height, spacing, and orientation is becoming central to agrivoltaic design practice, allowing designers to anticipate the energy–crop trade-off before construction rather than through costly field trial and error (Zainali et al., 2025). For this reason, agrivoltaics is increasingly treated as a design optimisation problem rather than a simple colocation strategy.

A second important issue is the choice of photovoltaic technology and module configuration (Małek et al., 2024; Polak et al., 2025; Šarkan et al., 2025). Monocrystalline and polycrystalline modules respond differently to irradiance, temperature, and thermal dissipation, especially under hot conditions. Comparative studies generally show that monocrystalline modules tend to achieve higher efficiency and power output, while polycrystalline modules are typically less efficient but remain widely used due to their lower cost and broad availability (Kilikevičienė et al., 2019; Supriyono et al., 2024). Beyond opaque crystalline silicon, the agrivoltaic literature increasingly considers semitransparent, bifacial, and reused PV modules as alternative means of reconciling electricity generation with crop light requirements: semitransparent and interspaced-cell modules can be tuned to transmit a controlled fraction of sunlight to the canopy (Montes-Romero et al., 2026), bifacial modules can capture additional rear-side irradiance reflected from the ground or interrow vegetation (Mouhib et al., 2024), and reused end-of-life modules have been shown to retain sufficient performance for agrivoltaic

deployment, which is particularly relevant for cost-sensitive developing regions (Nieto-Morone et al., 2025). In agrivoltaic systems more generally, module temperature is especially important because photovoltaic efficiency declines as temperature rises especially in arid climates (Adeeb et al., 2019; Odat, 2022), and even modest cooling can produce measurable gains in output and energy yield (Skoplaki and Palyvos, 2009). This makes the comparison of crystalline module technologies under elevated agrivoltaic mounting highly relevant for Baghdad’s climate, and situates the present monofacial crystalline-silicon comparison within a broader and rapidly diversifying technological landscape.

The agricultural side of agrivoltaics is equally important. Tomato is a high-value vegetable crop that is sensitive to heat and water stress, so it is a useful indicator species for evaluating whether agrivoltaics can support food production in hot-arid systems. Previous field studies have shown that tomato response under PV shading is strongly on microclimate, light reduction, and system design, with some studies reporting changes in fruit quality and yield rather than outright loss of yield (Ezzaeri et al., 2018). Comparable synergy between crop productivity and power generation has also been reported for other field crops under tuned agrivoltaic configurations, suggesting that yield-neutral or even yield-positive outcomes are achievable when shading intensity is matched to a crop’s physiological light requirements (Modi and Patel, 2024; Alomari et al., 2026).

Therefore, evaluating tomato under AV in Baghdad helps determine whether the system is agronomically acceptable as well as energetically beneficial. Another emerging dimension is the carbon intensity (Veselik et al., 2020; Ben Mariem et al., 2025; Lakhout et al., 2025). As interest in low-carbon agriculture grows, it is no longer sufficient to report only PV production or crop yield; systems should also be judged by carbon performance. Agrivoltaics can lower the intensity per unit electricity if elevated systems produce more energy over their inputs of lifetime, even if their structural materials are somewhat higher. Full life-cycle assessments of stilted and overhead agrivoltaic structures confirm that, despite the additional steel and foundation material required for elevated mounting, the land-sharing benefit and higher energy yield generally outweigh the added embodied burden relative to single-use agricultural or PV land (Krexner et

al., 2024; Cusenza et al., 2026). Recent design studies have also started to evaluate agrivoltaic systems through integrated energy, water, and carbon metrics, as well as combined land use indicators such as the land-equivalent ratio, underscoring the need for holistic assessment rather than single performance indicators (Warmann et al., 2024; Chopdar et al., 2024; Leon and Ishihara, 2018; Gosgot Angeles et al., 2026). This approach is especially relevant in Iraq, where the transition to cleaner electricity must also remain compatible with food production and adaptation to climate stress (IRENA, 2025).

Despite the rapid growth of agrivoltaic research, there is still limited field evidence from hot-arid cities such as Baghdad, particularly direct comparisons of elevated agrivoltaic and conventional ground-mounted PV systems using different crystalline technologies, and few studies simultaneously report electrical, thermal, carbon, and agronomic results from the same field trial.

Our study helps fill this gap by measuring module temperature, I–V characteristics, power output, efficiency, energy yield, carbon intensity, and tomato yield in a randomized field design. In doing so, it contributes evidence on whether agrivoltaics can function as a technically viable and agronomically acceptable strategy for Baghdad's climate while also improving the carbon and energy performance of solar systems in arid regions, and it discusses these findings in the context of the fast-moving international agrivoltaic literature on module technology, land use efficiency, and life-cycle carbon accounting.

This study presents a field-based case study conducted in the north of Baghdad, Iraq, during 2025. It aims at the following:

1. Quantify the impact of AV systems (using a tomato crop) on PV performance (panel efficiency, power gain, PV energy, carbon footprint and PV temperature improvement) of mono-crystalline and polycrystalline PV panels compared to conventional ground-mounted PV.
2. Evaluate the feasibility and yield of tomato cultivation under PV panels in the climate of Baghdad.
3. Estimate the potential reduction in carbon footprint (CO₂e) that can be achieved through the implementation of AV per unit energy.
4. Compare the relative performance of the Mono-Si and Poly-Si photovoltaic technologies within the AV system.
5. Compare the relative performance of mono-Si and poly-Si photovoltaic technologies in an AV system.

The results are intended to show whether AV mounting can improve PV output while supporting crop production, and how it might contribute to climate-change mitigation in Iraq and other arid regions.

METHODOLOGY

Study site and period

Measurements were taken on a private farm on the outskirts of Baghdad (approx. 33.3152° N, 44.3661° E) between 1 August and 30 September 2025, so the record starts in the hottest weeks and ends as autumn begins. The local climate is hot desert (Köppen BWh), with strong solar radiation and little rain. Mean values for the two months were 39.5 °C (air temperature) and 36.8% (relative humidity).

Experimental layout

Two separate experiments were run side by side. Experiment 1 tested the PV side: conventional ground-mounted arrays (C-PV) and elevated agrivoltaic arrays (AV) were each fitted with monocrystalline and polycrystalline modules, giving a 2 × 2 factorial analysed by two-way ANOVA. Its 720 observations covered panel efficiency, power gain, energy output, carbon intensity, and temperature improvement. Experiment 2 tested the crop side: tomato (*Solanum lycopersicum* L.) yield under the AV array was compared with an open-field control (C-Ag) by one-way ANOVA on 144 observations. In both experiments, means were separated with Tukey's HSD.

1. Control PV (C-PV): Mono-Si and Poly-Si arrays mounted close to the ground over uncultivated soil, height ≈ 1.0 m.
2. Agrivoltaic (AV-Mono & AV-Poly): Mono-Si and Poly-Si PV panels mounted at an elevated height (2.0 m clearance), with crops cultivated below.
3. Control Agriculture (C-Ag): Open-field cultivation of the same crop (no PV panels), representing conventional farming, replicated adjacent to the AV plots.

Instrumentation

Observation of the V curve by a PROVA-200 solar module analyser (TES Electrical Electronic Corp., Taipei, Taiwan) was used to trace the V curve of the solar panels. Measurement accuracy was $\pm 1\%$ of reading plus ± 9 mV for voltage and $\pm 1\%$ of reading plus ± 0.9 mA for current (depending on range). Solar irradiance measurement by a TES-132 solar energy meter (TES Electrical Electronic Corp., Taipei, Taiwan) was used to measure the intensity of solar radiation. Measurement precision was generally within ± 10 W/m² or $\pm 5\%$ of reading, whichever is greater, with an additional temperature-induced error of ± 0.38 W/m²/°C from 25 °C.

Solar irrigation pump by a 200 W solar pump (LSPI-12-20-2.5-200-1, Zhejiang Binter Electric Machinery Co., Ltd., Zhejiang, China) was used for irrigation. Maximum capacity was 2.5 m³/h.

PV operating temperature measurement by an LM35 temperature sensor (Texas Instruments, Dallas, USA) was used to measure the operating temperature of the photovoltaic panels. Measurement precision was typically ± 0.5 °C at 25 °C, with a linear output of 10 mV/°C. Operating range was -55 °C to $+150$ °C. Output type by analogue voltage directly compatible with Arduino analogue input pins.

PV operating temperature assessment using thermal imaging by a FLIR ONE Pro thermal imaging camera (FLIR Systems Inc., Wilsonville, Oregon, USA) was utilised. Thermal resolution was 160×120 pixels (19,200 points); measurement range was -20 °C to $+400$ °C, and accuracy ± 3 °C or $\pm 5\%$ of reading; thermal sensitivity was 150 mK, and field of view $55^\circ \times 43^\circ$.

Sampling and replication

To ensure statistical significance and reproducibility, each treatment combination was sampled six times a day at 30-minute intervals (12:00 to 14:30) throughout the experimental period. The data points for parameters such as

open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}) represent the mean of these daily measurements. This protocol yielded 180 copies per combination. During the experimental period, a total of 720 observations were recorded (Table 1).

Data analysis

Data were analysed using IBM SPSS Statistics v. 27. For the first experiment, a two-way analysis of variance was performed under a complete randomised block design at a significance level of $\alpha = 0.05$ to evaluate the effects of PV technology and mounting configuration on the measured variables. When significant differences were detected, Tukey's HSD test was applied for pairwise comparison of treatment means and within-factor interactions. For the second experiment, one-way analysis of variance was used at the same significance level to compare tomato yield between the AV and open-field control (C-Ag) treatments, with Tukey's HSD applied where appropriate to separate means.

PV efficiency (%)

The efficiency of the PV panel is the percentage of the power that the PV panel can produce compared to the power it can receive (Hatwaambo et al., 2007), Equation 1:

$$\eta = (FF \times I_{sc} \times V_{oc}) / (I_N \times A) \quad (1)$$

where: η is the efficiency of the PV panel (%); FF is the PV panel fill factor; I_{sc} is the short circuit current (A); V_{oc} is the open-circuit voltage (V); I_N is the incident solar radiation in the module (W/m²); and A is the actual active area of the module (m²).

Power gain (W)

The power gain represents the difference between the power produced by the PV modules within an Agrivoltaic system and the power produced by the PV modules, Equation 2:

Table 1. Summary of the first experiment design

Factor	Levels	Description
A: PV mounting	2	Control PV (C-PV), Agrivoltaic (AV-Mono & AV-Poly)
B: PV type	2	Monocrystalline (Mono-Si), Polycrystalline (Poly-Si)
Replications	180	6 daily mean measurements (12:00–14:30) $\times$ 3 panels per type $\times$ 10 replicates
Total sample (N)	720	$2 \times 2 \times 180 = 720$ observations

$$P_G = P_{AV} - P_{C-PV} \quad (2)$$

where: P_G is the net PV power (W); P_{AV} is the power produced by the PV module under the Agrivoltaic system (W); and P_{C-PV} is the power produced by the ground-mounted PV module (W).

PV energy (kWh)

The PV energy represents the total energy produced in one hour by a PV panel, Equation 3:

$$E_{PV} = P_{max} \times t \quad (3)$$

where: E_{PV} is the PV energy (kWh); P_{max} is the PV maximum power (W); and t is time (h).

Carbon footprint (g)

The carbon footprint represents the total greenhouse gas emissions (grams of CO₂ equivalent) associated with the electricity generated by the PV panels, Equation 4:

$$CFP_{PV} = E_{PV} \times n \times EF_{PV} \quad (4)$$

where: CFP_{PV} is the carbon footprint of the PV panel (g); E_{PV} is the PV panel energy output (kWh); n is the number of PV panels required to operate the solar irrigation pump; and EF_{PV} is the emission factor of the PV panel (44 g/kWh for monocrystalline; 50.1 g/kWh for polycrystalline) (Ardente et al., 2025).

Tomato yield (kg m⁻²)

The tomato yield represents the productivity of the crop per unit area.

PV temperature improvement (%)

This is the relative reduction in PV operating temperature when using an AV system compared to a conventional ground-mounted PV (C-PV) system, expressed as a percentage improvement, Equation 5:

$$T_i = (T_{C-PV} - T_{AV}) / T_{C-PV} \quad (5)$$

where: T_i is the temperature improvement (%); T_{C-PV} is the PV temperature in the conventional ground-mounted system (°C); and T_{AV} is the PV temperature in the Agrivoltaic system (°C).

RESULTS

The results presented below summarise the field measurements conducted in Baghdad, Iraq, from 1 August to 30 September 2025, quantifying the synergy between solar energy generation and tomato (*Solanum lycopersicum* L.) production in an extremely hot and dry climate (Köppen BWh). The average ambient temperature during the measurement period was 39.5 °C, with peaks exceeding 44 to 45 °C during the first half of August (Table 2). The study compared a conventional ground mounted (C-PV) installation with an elevated 2.0 m agrivoltaic (AV) installation for two silicon technologies: monocrystalline (Mono-Si) and polycrystalline (Poly-Si).

Thermal regulation and microclimate

Throughout the monitoring period, ground-mounted (C-PV) modules heated to an average of 76.3 °C, with a peak of 85 °C recorded during the first week of August, when ambient temperatures and irradiance were highest and cloud cover was minimal (Table 2). With the agrivoltaic (AV) configuration, the mean module temperature dropped to 63.5 °C - a reduction of 12.8 °C compared to the ground-mounted arrays. The seasonal pattern in Table 2 shows that this thermal gap was relatively stable throughout the two-month period (roughly 12–14 °C in early August, narrowing only slightly to about 11–13 °C in late September as ambient temperatures decreased), indicating that the cooling benefit of elevated mounting persisted even as background heat stress eased.

Two-factor ANOVA confirmed that this thermal improvement was overwhelmingly driven by mounting configuration ($F = 5130.499$; $p < 0.001$), with a smaller but still significant contribution from module type ($F = 9.146$; $p = 0.003$) and their interaction ($F = 9.146$; $p = 0.003$) (Table 3, Temp. Improvement column). Expressed as a relative metric, the average thermal improvement of AV modules over C-PV modules was 27.44%, and monocrystalline modules showed a marginally greater relative improvement (28.60%) than polycrystalline modules (26.29%) (Table 4).

The magnitude of the observed cooling (12.8 °C) is best explained by two reinforcing mechanisms operating simultaneously at the elevated AV site. First, the ≈ 2.0 m clearance below the AV modules allows greater airflow beneath and

Table 2. Baghdad ambient and PV panel operation temperatures (Aug 1 – Sep 30, 2025)

Date range	Ambient temp (°C)	C-PV temp (°C)	AV temp (°C)	Notes
Aug 1–5	43–44	82–85	68–71	Peak summer irradiance; minimal cloud cover
Aug 6–10	42–43	80–83	66–70	High insolation; slight humidity rise
Aug 11–15	41–42	78–82	65–69	Efficiency drop $\approx 0.4\%$ /°C
Aug 16–20	41–42	77–81	64–68	Stable irradiance; late summer plateau
Aug 21–25	40–41	76–80	63–67	Gradual cooling trend begins
Aug 26–31	40–41	75–79	62–66	Slightly lower insolation
Sep 1–5	39–40	74–78	61–65	Direct irradiance; minimal shading
Sep 6–10	38–39	73–76	60–64	Efficiency loss $\approx 0.4\%$ /°C
Sep 11–15	37–38	72–74	59–63	Humidity increase; mild cooling
Sep 16–20	37–38	71–73	58–62	Stable performance; convective cooling
Sep 21–25	36–37	70–72	57–61	Transition to autumn; lower insolation
Sep 26–30	33–35	68–71	55–59	End of season; minimal heat stress
Average	39.5	76.3	63.5	

around the panels, increasing convective heat loss relative to the C-PV arrays, which sit only ≈ 1.0 m above bare soil and are more exposed to reflected ground heat. Second, transpiration from the tomato canopy releases water vapour beneath the panels, and the resulting cooler, more humid microclimate increases convective heat dissipation from the underside of the modules, further limiting overheating relative to the bare soil C-PV control.

Conversion efficiency

Efficiency responded strongly to both mounting configuration and module type. The two-way ANOVA (Table 3, Efficiency column) demonstrated highly significant effects for mounting ($F = 1807.307$; $p < 0.001$), PV ($F = 121.415$; $p < 0.001$), and their interaction ($F = 117.945$; $p < 0.001$), confirming that the efficiency benefit of AV mounting was not uniform between technologies.

In both technologies, mean efficiency increased from 11.25% in C-PV to 15.39% under AV, an absolute gain of 4.14 percentage points (36.8% relative increase) (Table 4; Figure 1a–c). Disaggregated by technology, the Mono-Si panel achieved 16.45% efficiency under AV compared to 11.26% under C-PV (+5.19 points), while the Poly-Si panel achieved 14.32% under AV compared with 11.24% under C-PV (+3.08 points) (Table 4). The larger absolute and relative gain for monocrystalline modules indicates that Mono-Si cells are more sensitive to the AV-induced temperature reduction than Poly-Si cells, consistent with their generally lower series resistance and higher packing density.

Using the accepted negative temperature coefficient of efficiency for crystalline silicon ($\approx -0.45\%/^{\circ}\text{C}$) (Skoplaki and Palyvos, 2009), the observed 12.8 °C reduction in operating temperature alone would be expected to prevent a loss of approximately 5.76 percentage points of relative efficiency. This estimate is of the same

Table 3. Combined two-way ANOVA results for PV mounting and PV type on efficiency, power gain, energy, carbon footprint, and temperature improvement

Source	Efficiency (%)	Power gain (W)	Energy (kWh)	Carbon footprint (g CO _{2e} kWh ⁻¹)	Temp. improvement (%)
Mounting (F)	1807.307***	4625.876***	2301.085***	1907.404***	5130.499***
PV type (F)	121.415***	344.687***	195.798***	662.253***	9.146**
Mounting $\times$ PV type (F)	117.945***	344.687***	166.130***	26.110***	9.146**
Error (Mean square)	1.707	44.021	8.940×10^{-5}	41.725	26.425

Note: F-values shown; *** $p < 0.001$, ** $p < 0.01$. Degrees of freedom are identical across all five models (Mounting = 1, PV type = 1, Interaction = 1, Error = 716, Total = 719; $n = 720$).

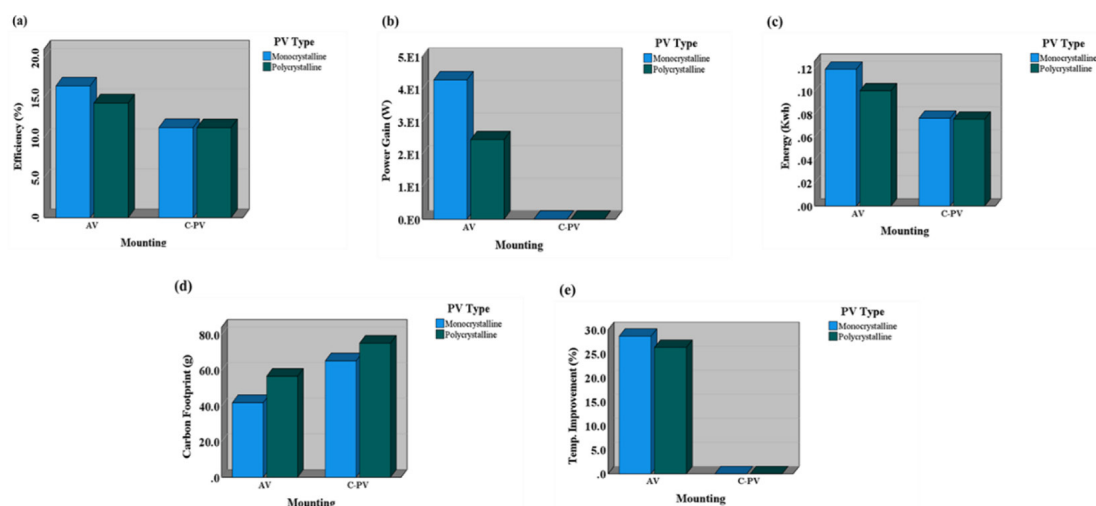


Figure 1. Combined effects of PV installation and PV type on (a) efficiency (%), (b) power gain (W), (c) energy (kWh), (d) carbon footprint (g CO_{2e} kWh⁻¹), and (e) temperature improvement (%)

order as the measured gain, suggesting that thermal regulation is the dominant – though not the improvement in sole – mechanism behind the AV efficiency improvement; the residual difference may reflect additional factors such as reduced dust / soil accumulation on elevated modules and small differences in effective irradiance geometry between the two mounting heights.

Power and energy

The power output followed the same pattern as efficiency. The mean power gain of the AV modules over the C-PV modules was 33.64 W per panel ($F = 4625.876$; $p < 0.001$) (Table 3, Power Gain column; Figure 1b). The AV-Mono configuration produced the largest gain, 42.82 W per panel, while AV-Poly produced 24.45 W per panel (Table 4), again showing that monocrystalline modules capture proportionally more benefit from elevated mounting. The energy yield mirrored the power gain results. The mean generation of electricity per measurement window increased from 0.08 kWh under C-PV to 0.11 kWh under AV ($F = 2301.085$; $p < 0.001$) (Table 3, Energy column; Figure 1c). The AV-Mono configuration reached 0.12 kWh, a 50% increase relative to the C-PV baseline of 0.08 kWh, while AV-Poly reached 0.10 kWh, a 25% increase over the same baseline (Table 4).

Operational carbon footprint

Both the mounting configuration ($F = 1907.404$; $p < 0.001$) and the PV type ($F =$

662.253; $p < 0.001$) significantly affected the operational carbon intensity of the generated electricity (Table 3, Carbon Footprint column; Figure 1d). The mean intensity of carbon decreased from 70.26 g CO_{2e}/kWh under C-PV to 49.23 g CO_{2e}/kWh under AV, a reduction of 29.9% (Table 4). At the technology level, the AV-Mono combination achieved the lowest carbon intensity of the four treatments (41.80 g CO_{2e} / kWh), while the C-PV Poly combination recorded the highest (75.22 g CO_{2e}/kWh) (Table 4). Because the underlying emission factors used in Equation (4) are fixed per technology (44 g/kWh for monocrystalline and 50.1 g/kWh for polycrystalline) (Ardente et al., 2025), the entire reduction in carbon intensity observed under AV mounting is attributable to the increase in energy yield achieved from the same nominal installed capacity, rather than to any change in embodied emissions per module.

Tomato yield and agronomic outcome

The one-way ANOVA comparing cultivation systems showed a mean tomato yield of 3.635 kg/m² in the open-field control (C-Ag) versus 3.452 kg/m² under the agrivoltaic system (AV) – a difference of 0.183 kg/m², or approximately 5% (Table 5, Figure 2). The associated F-statistic ($F = 3.794$; $p = 0.053$) falls just above the conventional $\alpha = 0.05$, indicating that the yield difference between the two systems was not statistically significant, although the result is close to the limit and

Table 4. Combined summary of the measured performance parameters by treatment combination, mounting configuration, and PV type

Group	Efficiency (%)	Power gain (W)	Energy (kWh)	Carbon footprint (g CO ₂ e kWh ⁻¹)	Temp. improvement (%)
<i>By treatment combination (Mounting × PV type)</i>					
AV – Monocrystalline	16.45	42.82	0.12	41.80	28.60
AV – Polycrystalline	14.32	24.45	0.10	56.65	26.29
C-PV – Monocrystalline	11.26	0.00	0.08	65.29	0.00
C-PV – Polycrystalline	11.24	0.00	0.08	75.22	0.00
<i>By mounting configuration (marginal mean)</i>					
AV	15.39	33.64	0.11	49.23	27.44
C-PV	11.25	0.00	0.08	70.26	0.00
<i>By PV type (marginal mean)</i>					
Monocrystalline	13.85	21.41	0.10	53.55	14.30
Polycrystalline	12.78	12.23	0.09	65.94	13.14

should be interpreted with appropriate caution rather than as an unambiguous equivalence.

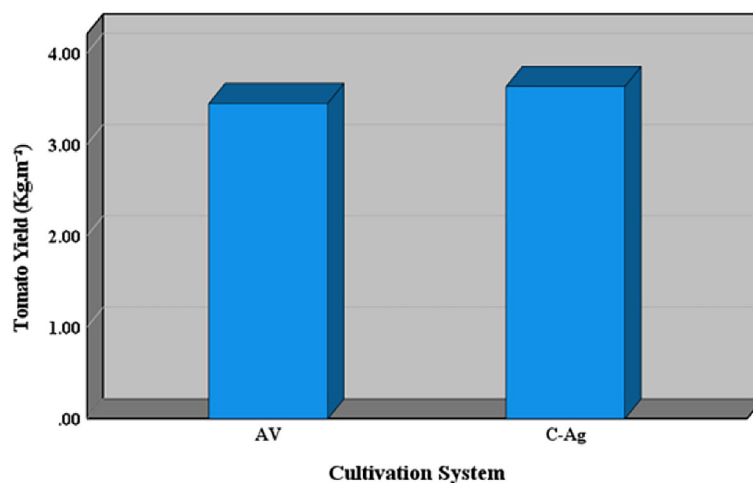
The near-significant F-statistic (3.794) suggests a modest downward trend in yield below the elevated panels, but the p-value (0.053) confirms that this difference cannot be distinguished from sampling variability at the conventional significance level. In practical terms, the AV system preserved approximately 95% of open field productivity while simultaneously generating the electrical benefits.

Temperature improvement (%)

The temperature-improvement metric expresses, for each treatment, the percentage reduction in module operating temperature relative to the C-PV baseline and therefore provides a normalised complement to the absolute temperatures. The two-way ANOVA (Table 3, Temp. Improvement column) confirms that mounting configuration is by far the dominant source of variation ($F = 5130.499$; $p < 0.001$), an effect approximately two orders of magnitude greater than that of PV type ($F = 9.146$;

Table 5. One-way ANOVA results for cultivation system on tomato yield (kg m⁻²)

Source	df	Sum of squares	Mean square	F	Sig.
Cultivation system	1	1.212	1.212	3.794	0.053
Error	142	45.360	0.319		
Total	143	46.572			

**Figure 2.** Effect of cultivation system on tomato yield (kg m⁻²)

$p = 0.003$) or the mounting $\times$ PV type mounting ($F = 9.146$; $p = 0.003$). This pattern is even more pronounced than for efficiency and power, reinforcing that thermal management – rather than module chemistry – is the main lever available to designers of hot-arid agrivoltaic systems.

At the level (Table 4), AV-Mono achieved the greatest relative improvement (28.60%), followed by AV-Poly (26.29%), while the two ground-mounted treatments show 0% improvement by definition, since C-PV is the reference baseline against which AV performance is expressed. Averaged between PV types, AV mounting delivered a 27.44% mean temperature improvement relative to C-PV (Table 4), consistent with the absolute reduction. This asymmetry is visually apparent in Figure 1e, where the AV bars for both technologies rise well above the near-zero C-PV bars, while the gap between the two PV types within each mounting configuration is comparatively small – a pattern that visually corroborates the ANOVA result that the PV type explains only a minor share of the variance relative to mounting configuration.

The marginally larger relative improvement recorded for monocrystalline modules (28.60% vs. 26.29%, Table 5) is consistent with the lower resistance in series and higher packing density, which likely allow Mono-Si cells to respond more readily to the enhanced convective and evapotranspirative cooling environment created beneath the crop canopy. This cooling mechanism is illustrated directly in Figure 3, where the thermal image shows markedly lower surface temperatures across the AV modules and the shaded canopy beneath them compared to the exposed C-PV array and bare soil, visually corroborating the 12.8 °C differential and the relative improvement quantified in Table 5. Taken together, the ANOVA (Table 3), the treatment means (Table 5), and the

thermal imagery (Figure 3) provide converging quantitative and visual evidence that elevated agrivoltaic mounting – rather than PV technology choice – is the principal driver of thermal regulation in Baghdad’s hot-arid climate.

DISCUSSION

The results confirm that elevated agrivoltaic mounting delivers a coherent chain of benefits in Baghdad’s hot-arid climate, from module cooling, through electrical efficiency and energy yield, to reduced operational carbon intensity, while imposing no statistically significant agronomic penalty on tomato production. The sections below interpret these findings in relation to the broader and rapidly evolving, international literature on agrivoltaic system design, land use efficiency, and life-cycle carbon accounting throughout the lifecycle.

Thermal regulation in extreme arid climates

The mean temperature reduction measured under AV mounting is substantially higher than the 3–7 °C typically reported for agrivoltaic installations in temperate climates. This is consistent with and quantitatively extends, the conclusions of Barron-Gafford et al. (2019) and Hassanpour Adeh et al. (2018), who found that agrivoltaic systems provide the greatest microclimatic and thermal benefits in hot, dry environments where the baseline thermal load on ground-mounted modules is highest. The mechanism inferred from the present data set – enhanced convective cooling from greater panel clearance combined with evapotranspiration-driven humidification of the under-panel microclimate – is consistent with the

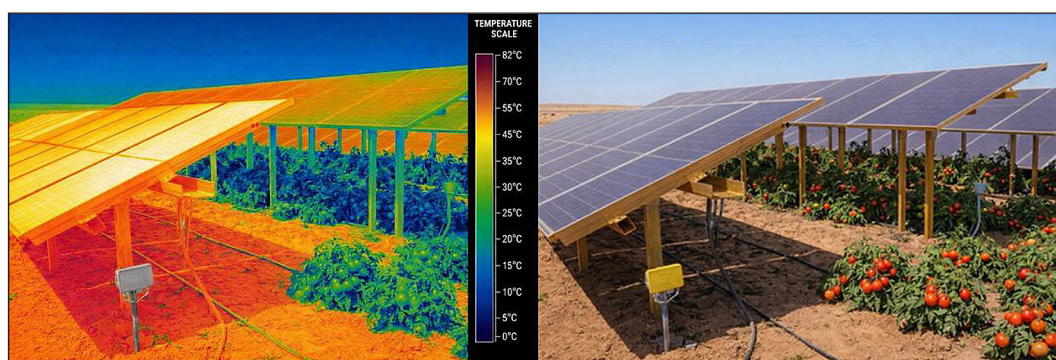


Figure 3. Microclimatic effects of crops on PV panel temperature

canopy geometry effects described for stilted and vertical bifacial agrivoltaic structures, where elevation and airflow path around the array strongly influence the achievable thermal benefit (Krexner et al., 2024). This suggests that the 2.0 m clearance adopted in this study, while effective, is itself a design variable whose optimum for hot-arid climates has not yet been established and would benefit from systematic testing against the height-sensitivity relationships reported in agrivoltaic modelling reviews (Zainali et al., 2025).

Efficiency – cooling and module type

The average efficiency increase of 4.14 percentage points (11.25% → 15.39%) is close to, but somewhat larger than, the theoretical gain predicted from the temperature coefficient of crystalline silicon alone ($-0.45\%/^{\circ}\text{C} \times 12.8^{\circ}\text{C} \approx 5.76\%$ relative improvement), suggesting that thermal regulation explains most, but not all, of the observed benefit. The stronger response of monocrystalline modules (+5.19 points) compared to polycrystalline modules (+3.08 points) mirrors the technology-dependent sensitivity to cooling reported by Supriyono et al. (2024), who also found monocrystalline modules are more responsive to active and passive cooling interventions than polycrystalline modules, probably reflecting differences in cell packing density, series resistance, and grain-boundary losses between the two technologies.

It is worth situating this monofacial crystalline-silicon comparison within the wider set of module technologies that are currently being evaluated for agrivoltaic use. Semitransparent and interspaced cell modules can be engineered to transmit a controlled fraction of light to the crop canopy, offering a design lever to balance electrical output against agronomic light requirements that opaque monocrystalline and polycrystalline modules do not provide (Montes-Romero et al., 2026). Likewise, bi-facial modules exploit rear-side irradiance reflected from the ground, interrow vegetation, or elevated structure, and have been shown to meaningfully increase energy yield in agrivoltaic olive-grove trials without additional land take (Mouhib et al., 2024). Because the present study used standard monofacial modules, it was not able to capture this rear-side gain; given Baghdad's high ground albedo during the dry season, bifacial gain could plausibly add a further increment to the AV energy yield beyond

what is reported here and represents a promising avenue for follow-up trials. Reused, end-of-life PV modules have also been shown to retain adequate performance for agrivoltaic deployment (Nieto-Morone et al., 2025), which may be particularly relevant for lowering the capital cost of AV adoption in Iraq and other developing regions where financing elevated mounting structures is a practical barrier.

Power output, energy yield, and land-use implications

The measured power gain (mean 33.64 W per panel, up to 42.82 W for AV-Mono) and the corresponding 37.5% increase in mean energy yield (0.08 → 0.11 kWh per measurement window) demonstrate that, for the same nominal installed capacity, elevated mounting alone – without any change in module technology – can materially increase electricity output in a hot-arid setting. This finding reinforces the broader case for agrivoltaics as a land-use efficiency strategy: recent regional case studies have shown that combining PV generation with cropping in various configurations increases the effective productivity of a given land parcel relative to single-use PV or agricultural land (Gosgot Angeles et al., 2026). However, the present study quantified energy and crop results separately rather than through a unified land equivalent ratio (LER) or comparable functional unit; Adopting such integrated metrics, as recommended by Leon and Ishihara (2018) and applied in several recent land use efficiency studies (Gosgot Angeles et al., 2026), would allow Baghdad results to be compared more directly with agrivoltaic trials conducted elsewhere and is recommended for future work at this site. The consistency of the measured power and energy gains with model-based expectations from recent agrivoltaic simulation reviews (Zainali et al., 2025; Warmann et al., 2024) also supports the use of this data set to validate or calibrate design tools for other hot-arid locations, such as Türkiye.

Operational carbon footprint and life-cycle considerations

The 29.9% reduction in operational carbon intensity under mounting of AV ($70.26 \rightarrow 49.23 \text{ g CO}_2\text{e kWh}^{-1}$) is a direct arithmetic consequence of a higher energy yield divided over a fixed embodied emission factor per module

(Ardente et al., 2025), and the lowest carbon intensity was recorded for the combination of AV-Mono ($41.80 \text{ g CO}_2\text{e kWh}^{-1}$), consistent with the lower manufacturing emission factor ($44 \text{ vs. } 50.1 \text{ g kWh}^{-1}$) reinforcing, rather than offset, its efficiency advantage. It is important to note, however, that the carbon metric applied in this study is an operational, energy-normalised intensity rather than a full cradle-to-grave life-cycle assessment. Comparative LCA studies of stilted and overhead agrivoltaic structures show that the additional steel, foundations, and mounting material required for elevated arrays add a nontrivial embodied-carbon burden relative to ground-mounted PV, even though this burden is typically outweighed over the system lifetime by the combined benefit of land-sharing and higher energy yield (Krexner et al., 2024; Cusenza et al., 2026). Because the present analysis did not account for the structural material footprint of the elevated AV mounting frame, the true net carbon benefit of the Baghdad AV system relative to C-PV is likely somewhat smaller than the 29.9% operational figure reported here, and a complete LCA – following the harmonised PV carbon footprint methodology of Ardente et al. (2025) and the overhead agrivoltaic LCA framework of Cusenza et al. (2026) – is recommended as a priority extension of this work. However, these findings align with the broader conclusion of recent sustainability assessments that agrivoltaics can lower the effective carbon intensity of solar electricity when the additional energy captured through improved thermal management is properly accounted for (Lakhout et al., 2025).

Agronomic performance and crop–energy trade-offs

The absence of a statistically significant yield difference between AV (3.452 kg m^{-2}) and open field control (3.635 kg m^{-2}) ($p = 0.053$) is consistent with earlier findings that moderate PV shading does not necessarily translate into an overall loss for tomato, and can even mitigate photooxidative stress and sunburn under intense summer irradiance (Ezzaeri et al., 2018). Because the light saturation point lies below the full irradiance available during Baghdad’s summer, the partial shading imposed by the elevated AV structure likely removed ‘excess’ light that could not be fully utilised photosynthetically, while the associated reduction in soil evaporation and

heat stress beneath the panels partially compensated for the reduction in incident radiation. This crop-specific balance between shading and productivity echoes the synergy reported for other field crops under tuned agrivoltaic configurations, where appropriately matched shading intensity produced yield outcomes statistically indistinguishable from, or in some cases better than, open field controls while simultaneously generating substantial power output (Modi and Patel, 2024). The marginal p -value obtained here (0.053) nevertheless indicates that the yield trend is close to the significance threshold, and a longer observation window spanning multiple growing seasons would be needed to confirm whether the small yield gap is a genuine and consistent effect of AV shading or simply sampling variability within a single 60-day trial.

Limitations and future work

Several limitations should be considered when generalising these findings. First, the trial covered a single 60-day window within one growing season and one crop, so interannual and inter-seasonal variability in irradiance, temperature, and crop response was not captured. Second, only monofacial crystalline silicon technologies were tested; Given the demonstrated potential of semitransparent modules (Montes-Romero et al., 2026) and bifacial modules (Mouhib et al., 2024) to further improve the energy–crop balance, comparative trials incorporating these technologies at the same Baghdad site would meaningfully extend the present results. Third, the carbon footprint indicator used here is an operational, energy-normalised metric rather than a full life-cycle assessment; incorporating the embodied emissions of the elevated mounting structure, following recent overhead-agrivoltaic LCA methodologies (Krexner et al., 2024; Cusenza et al., 2026), would provide a more complete picture of net climate benefit. Fourth, land use outcomes were reported as separate energy and yield metrics rather than as an integrated land equivalent ratio or comparable functional unit (Leon and Ishihara, 2018; Gosgot Angeles et al., 2026), limiting direct comparability with international agrivoltaic benchmarks. Finally, the use of reused or second-life PV modules – shown elsewhere to retain adequate agrivoltaic performance (Nieto-Morone et al., 2025) – was not evaluated but could offer a

cost-effective pathway for scaling AV adoption in Iraq, where capital cost is likely to be a key barrier to deployment. Addressing these gaps in subsequent field seasons would strengthen the evidence base for agrivoltaic policy and investment decisions in hot-arid regions.

CONCLUSIONS

On a 2 m frame above tomatoes, PV modules in Baghdad ran 12.8 °C cooler than ground-mounted ones (63.5 vs 76.3 °C). That is far more than the 3–7 °C typical of temperate sites, and it supports the view that agrivoltaic cooling grows with heat stress. Mounting, module type and their interaction were significant for every indicator ($p < 0.01$, mostly $p < 0.001$), so designers should choose the structure and the technology together.

Cooler modules worked better. Efficiency rose from 11.25% to 15.39% (mono-Si 11.26% → 16.45%; poly-Si 11.24% → 14.32%), power by 33.64 W per panel on average (42.82 W for AV-Mono), and energy per measurement window from 0.08 to 0.11 kWh (0.12 kWh for AV-Mono). With emission factors held fixed, the extra energy cut operational carbon intensity by 29.9% (70.26 → 49.23 g CO₂e kWh⁻¹); AV-Mono was lowest at 41.80 g CO₂e kWh⁻¹. Mono-Si beat poly-Si on every electrical and carbon measure, but both benefited from elevation.

None of this came at the cost of the crop, at least within the precision of one season. Tomato yield under the frame (3.452 kg m⁻²) was not significantly different from the open field (3.635 kg m⁻²; $p = 0.053$). Given how close p is to 0.05, we would want at least one more season before calling the yields equivalent.

In general, the results support agrivoltaics as a technically robust and agronomically compatible strategy to reconcile electricity generation with food production in hot-arid regions such as central Iraq or central Türkiye, and are broadly consistent with, and extend, the recent international literature on agrivoltaic thermal performance, module technology, land-use efficiency, and life-cycle carbon accounting. At the same time, the study's operational (rather than full life-cycle) carbon accounting, its exclusive focus on monofacial crystalline-silicon modules, its single-season agronomic dataset, and its lack of an integrated land equivalent ratio metric point to clear priorities for future research,

including a full cradle-to-grave life-cycle assessment of the elevated mounting structure, trials of bifacial and semitransparent modules, multi-season agronomic monitoring, and adoption of standardised land-use efficiency indicators, all of which would further strengthen the evidence base for agrivoltaic deployment in Iraq and comparable arid environments such as Türkiye.

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