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Photovoltaic modules performance and carbon footprint assessment in agrivoltaic system

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ABSTRACT

A two-month field trial (1 August–30 September 2025) was conducted on a farm near Baghdad to investigate how elevating PV modules above a crop affects their electrical output, operational carbon intensity. 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 CO_2e 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 Adeh 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 co-location 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). Mono- and polycrystalline modules do not react in the same way to irradiance, heat, and heat dissipation, and the difference shows most in hot weather. In most comparisons monocrystalline modules give higher efficiency and power, whereas polycrystalline modules are less efficient but stay common because they are cheaper and easy to obtain (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 & Palyvos, 2009). For Baghdad, then, it matters which crystalline module is placed on an elevated frame, and our two-technology comparison is one small piece of a field where module options are multiplying quickly.

Food production is the other half of the question. We picked tomato because it is a cash crop for local growers and is easily hurt by heat and water shortage; if it copes under panels, many other summer vegetables probably will too. How tomato responds to PV shade has been shown to hinge on local microclimate, on how much light the structure intercepts and on array geometry, and in several trials the main change was in fruit quality and yield components rather than an outright drop in yield (Ezzaeri et al., 2018). Work on other field crops points the same way: when shade is matched to what the crop actually needs, yields can stay at open-field level or even rise slightly (Modi & Patel, 2024; Alomari et al., 2026). The tomato trial in Baghdad was therefore meant to answer a grower's question as well as an engineer's one.

Another emerging dimension is carbon intensity (Veselík et al., 2020; Ben Mariem et al., 2025; Lakhouit et al., 2025). With growing attention to low-carbon farming, reporting electricity output or crop yield alone is no longer enough, and the carbon cost of each system also has to be measured. In principle, an elevated array can still come out ahead on carbon per kWh, even though it uses more steel, as long as it generates enough extra energy over its service life. 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). Several recent design

studies combine energy, water, and carbon indicators, or use joint land-use measures such as the land-equivalent ratio, instead of judging a system by one number (Warmann et al., 2024; Chopdar et al., 2024; Leon & Ishihara, 2018; Gosgot Angeles et al., 2026). That kind of multi-indicator view fits the Iraqi case well, because any shift to cleaner power there has to coexist with food production and with adaptation to a hotter climate (IRENA, 2025).

Measurements from cities as hot and dry as Baghdad remain rare. In particular, few trials have set elevated AV arrays against conventional ground-mounted arrays using more than one crystalline technology, and fewer still have reported electrical, thermal, carbon, and crop results from a single experiment.

The present trial addresses this gap. In one randomised field layout we measured module temperature, I–V curves, power, efficiency, energy yield, carbon intensity, and tomato yield. 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 international agrivoltaic literature on module technology, land-use efficiency, and life-cycle carbon accounting.

It aims to:

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 monocrystalline 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 (CO_2e) per unit energy that can be achieved through the implementation of AV.
4) Compare the relative performance of Mono-Si and Poly-Si photovoltaic technologies within the AV system.
5) 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.

- Control PV (C-PV): Mono-Si and Poly-Si arrays mounted close to the ground over uncultivated soil, height ≈ 1.0 m.
- 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.
- Control Agriculture (C-Ag): Open-field cultivation of the same crop (no PV panels), representing conventional farming, replicated adjacent to the AV plots.

Instrumentation

I–V curve tracing: a PROVA-200 solar module analyser (TES Electrical Electronic Corp., Taipei, Taiwan) was used to trace the I–V curve of the solar panels. Measurement accuracy: ±1% of reading plus ±9 mV for voltage and ±1% of reading plus ±0.9 mA for current (depending on range).

Solar irradiance measurement: a TES-132 solar energy meter (TES Electrical Electronic Corp., Taipei, Taiwan) was used to measure the intensity of solar radiation. Measurement precision: generally within ±10 W/m² or ±5% of reading, whichever is greater, with an additional temperature-induced error of ±0.38 W/m²/°C from 25 °C.

Solar irrigation pump: 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: 2.5 m³/h.

PV operating temperature measurement: an LM35 temperature sensor (Texas Instruments, Dallas, USA) was used to measure the operating temperature of the photovoltaic panels. Measurement precision: typically ±0.5 °C at 25 °C, with a linear output of 10 mV/°C. It works between −55 and +150 °C and gives an analogue voltage that can be read directly by the analogue pins of an Arduino board.

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 (Voc) and short-circuit current (Isc) represent the mean of these daily measurements. In total, each treatment combination received 180 replicate observations, giving 720 observations over the experimental period (Table 1).

Data analysis

All statistics were run in IBM SPSS Statistics 27. In experiment 1, two-way ANOVA (randomised complete block design, α = 0.05) tested whether PV technology, mounting configuration and their interaction affected each measured variable. 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 agrivoltaic (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):

$$\eta = (FF \times I_{SC} \times V_{OC}) / (I_N \times A) \times 100 \quad (1)$$

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 on the module (W/m²); and A is the active area of the module (m²).

Power gain (W)

The power gain represents the difference between the power produced by the PV modules within the agrivoltaic system and the power produced by the ground-mounted PV modules, Equation (2):

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

where: P_G is the net PV power gain (W); P_{AV} is the power produced by the PV module under the agrivoltaic system (W); and $P_{C\text{-}PV}$ 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):

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

Table 1. Factors, levels, and replication in Experiment 1

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) × 3 panels per type × 10 replicates
Total sample (N)	720	2 × 2 × 180 = 720 observations

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

Carbon footprint (g)

The carbon footprint represents the total greenhouse gas emissions (grams of CO_2 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 agrivoltaic (AV) system compared to a conventional ground-mounted PV (C-PV) system, expressed as a percentage improvement, Equation (5):

$$T_i = [(T_{C\text{-}PV} - T_{AV}) / T_{C\text{-}PV}] \times 100 \quad (5)$$

where: T_i is the temperature improvement (%); $T_{C\text{-}PV}$ 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). On the AV structure the modules averaged 63.5 °C, 12.8 °C cooler than the ground-mounted arrays. Table 2 shows that this gap hardly changed over the season: it was about 12–14 °C in early August and still 11–13 °C in late September, when the air had cooled. Elevation therefore kept the modules cooler even after the peak heat had passed.

In the two-way ANOVA, mounting configuration accounted for almost all of the variation in temperature improvement ($F = 5130.499$; $p < 0.001$). Module type and the mounting × type interaction also reached significance (both $F = 9.146$, $p = 0.003$; Table 3), but their effects were tiny next to that of mounting. As a relative value, AV modules ran 27.44% cooler than C-PV modules, with 28.60% for monocrystalline and 26.29% for polycrystalline modules (Table 4).

We attribute the 12.8 °C cooling to two effects that act together on the elevated array. First, the ≈ 2.0 m clearance below the AV modules allows greater airflow beneath and 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. The second is the crop itself: water transpired by the tomato plants humidifies and cools the air just under the modules, so their rear surfaces lose heat faster than those of the C-PV modules, which sit over dry, bare soil.

Conversion efficiency

Both factors changed efficiency markedly. Mounting ($F = 1807.307$), PV type ($F = 121.415$) and their interaction ($F = 117.945$) were all significant at $p < 0.001$ (Table 3), so

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 ≈ 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 ≈ 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	

Table 3. Two-way ANOVA (F-values) for the effects of mounting configuration and PV type on efficiency, power gain, energy, carbon intensity, and temperature improvement

Source	Efficiency (%)	Power gain (W)	Energy (kWh)	Carbon footprint (g CO2e 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 × 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 <.001, ** p <.01. Degrees of freedom are identical across all five models (Mounting = 1, PV type = 1, Interaction = 1, Error = 716, Total = 719; n = 720).

the benefit of the AV frame was not the same for the two technologies.

Across 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 5; 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 5). 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.

How much of this can cooling alone explain? Taking a temperature coefficient of about −0.45%/°C for crystalline silicon (Skoplaki & Palyvos, 2009), 12.8 °C of cooling should lift efficiency by roughly 5.8% of its own value, which is only about 0.65 points when efficiency is near 11%. Most of the 4.14-point gain therefore has some other origin. We suspect less dust and soil on the raised modules and a different irradiance geometry at the two heights, but neither was measured in this trial.

Power and energy

Power output told the same story. 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 gain was largest for AV-Mono (42.82 W per panel) and smaller for AV-Poly (24.45 W per panel) (Table 5), so the monocrystalline modules again profited more from elevation.

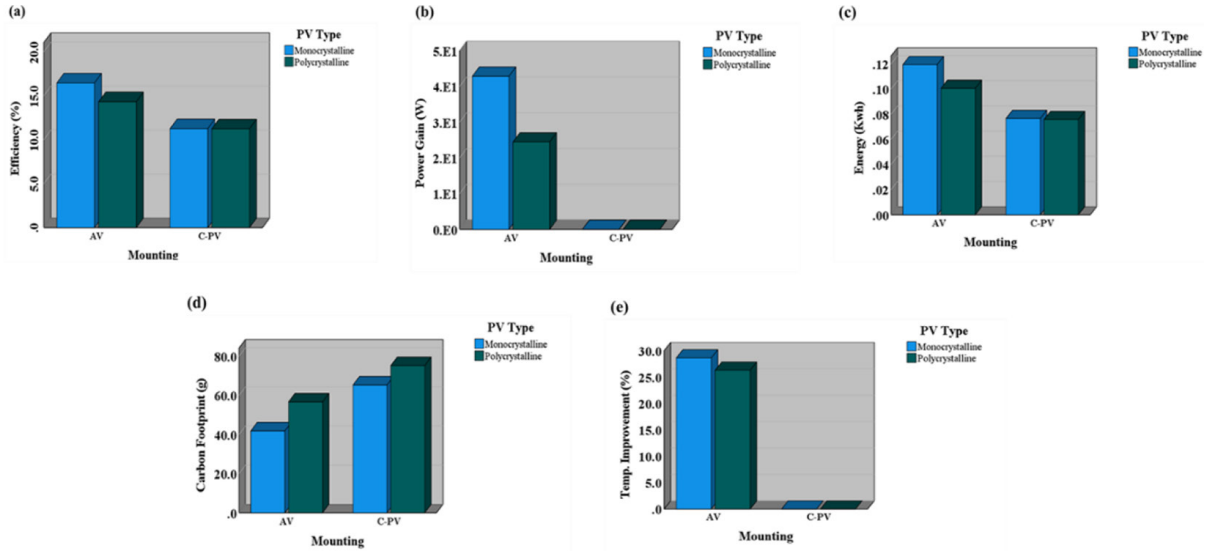


Figure 1. Combined effects of PV installation and PV type on (a) efficiency (%), (b) power gain (W), (c) energy (kWh), (d) carbon footprint (g CO_{2e} kWh^{-1}), and (e) temperature improvement (%)

Table 4. One-way ANOVA results of tomato yield (kg m^{-2}) for the two cultivation systems

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			

Table 5. Treatment means and marginal means (by mounting and by PV type) of all measured parameters

Group	Efficiency (%)	Power gain (W)	Energy (kWh)	Carbon footprint (g CO2e kWh^{-1})	Temp. improvement (%)
By treatment combination (Mounting × PV type)					
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
By mounting configuration (marginal mean)					
AV	15.39	33.64	0.11	49.23	27.44
C-PV	11.25	0.00	0.08	70.26	0.00
By PV type (marginal mean)					
Monocrystalline	13.85	21.41	0.10	53.55	14.30
Polycrystalline	12.78	12.23	0.09	65.94	13.14

Energy yield followed the power results. Per measurement window, mean output rose from 0.08 kWh on C-PV to 0.11 kWh on AV ($F = 2301.085$; $p < 0.001$; Table 3; Figure 1c). AV-Mono produced 0.12 kWh, 50% above the 0.08 kWh C-PV baseline, and AV-Poly produced 0.10 kWh, 25% above it (Table 5).

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 carbon intensity 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 5). At the technology level, the AV-Mono combination achieved the lowest carbon intensity of the four treatments (41.80 g CO2e/kWh), while the C-PV-Poly combination recorded the highest (75.22 g CO2e/kWh) (Table 5). 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 4, Figure 2). The ANOVA gave F = 3.794 and p = 0.053. Strictly, that is not significant at the 0.05 level, but it is close enough that we would not claim the two systems yield the same.

Yield was a little lower under the panels, yet with p = 0.053 we cannot rule out plot-to-plot variation as the cause. In practice, the AV plots gave about 95% of the open-field yield while also producing the electrical gains described above.

Temperature improvement (%)

Temperature improvement is the percentage fall in module temperature relative to C-PV; it puts the absolute temperatures reported above on a common relative scale. Here the dominance of mounting is even clearer than for efficiency or power: its F-value (5130.499; $p < 0.001$) is several hundred times those of module type and of the interaction (both 9.146; p = 0.003; Table 3). For anyone designing an agrivoltaic array in a hot-arid climate, then, the structure matters far more than the cell technology.

By definition, both C-PV treatments score 0% because they are the reference. Of the AV treatments, AV-Mono improved most (28.60%) and AV-Poly slightly less (26.29%), giving 27.44% for AV overall (Table 5); this agrees with the 12.8 °C absolute drop reported earlier. Figure 1e makes the point visually: the two AV bars stand well above the C-PV bars, while the two technologies differ only a little within each mounting, just as the ANOVA suggests.

Monocrystalline modules showed a slightly greater improvement than polycrystalline modules (28.60% versus 26.29%; Table 5). Their lower series resistance and denser cell packing may allow them to benefit more from the convective and evaporative cooling that occurs beneath the vegetation cover. Both analysis of

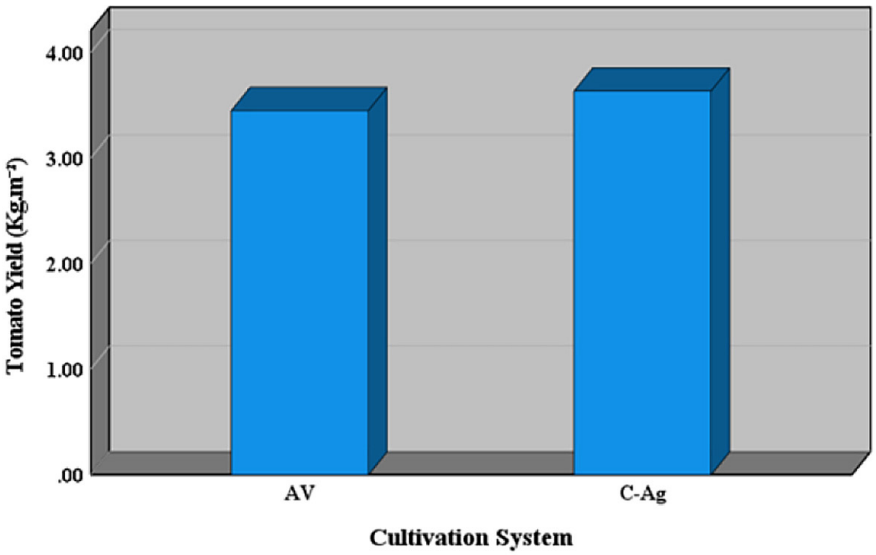


Figure 2. Tomato yield (kg m^{-2}) in the AV plots and in the open-field control (C-Ag)

variance (ANOVA) and mean values for the individual variants lead to the consistent conclusion that, under the conditions in Baghdad, it is the mounting height, rather than the type of module – that determines the operating temperature of the modules.

DISCUSSION

Put simply, raising the modules over the crop cooled them, which raised efficiency and energy output and lowered carbon intensity per kWh, and it did so without a statistically detectable loss of tomato yield. Below we compare each of these outcomes with published agrivoltaic work on design, land-use efficiency and life-cycle carbon.

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 canopy geometry effects described for stilted and vertical bifacial agrivoltaic structures, where elevation and the 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

Efficiency rose by 4.14 points on average (11.25% → 15.39%). As noted in the Results, a −0.45%/°C coefficient applied to 12.8 °C of cooling accounts for only about 0.65 points of this, so most of the improvement must come from elsewhere, possibly cleaner surfaces or the irradiance geometry, neither of which we measured. The gap between technologies (+5.19 points for mono-Si, +3.08 for poly-Si) resembles what Supriyono et al. (2024) observed, namely that monocrystalline modules respond more to both active and passive cooling; differences in packing density, series resistance and grain-boundary losses are the likely reasons.

Only monofacial crystalline modules were tested here, whereas several other module types are now being tried in agrivoltaic settings. Semitransparent and interspaced-cell modules can be engineered to transmit a controlled fraction of light to the crop canopy,

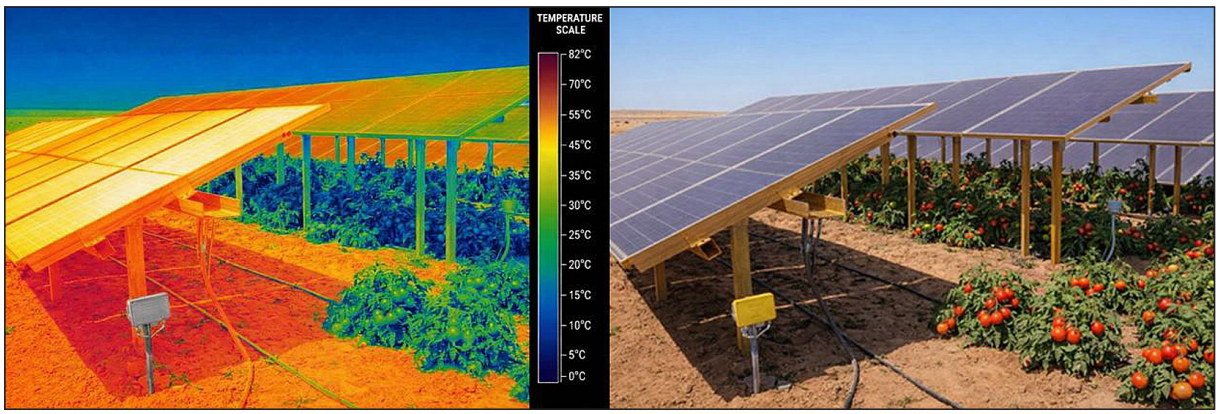


Figure 3. Agrivoltaic array over the tomato crop: infrared image (left) and ordinary photograph (right)

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, bifacial 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 the 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 AV mounting (70.26 → 49.23 g CO2e 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 AV-Mono combination (41.80 g CO_2e kWh^{-1}), consistent with the lower manufacturing emission factor (44 vs. 50.1 g kWh^{-1}) reinforcing, rather than offsetting, 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. Nevertheless, 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 (Lakhouit 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 the 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 photo-oxidative stress and sunburn under intense summer irradiance (Ezzaeri et al., 2018). During a Baghdad summer, midday irradiance exceeds the light-saturation point of tomato leaves, so part of the light removed by the panels could not have been used for photosynthesis anyway. The shade also cut soil evaporation and plant heat stress beneath the frame, which would have compensated for some of the lost radiation. A similar balance between shade and yield has been described for other field crops: when the degree of shading suited the crop, yields matched or exceeded those of open-field controls while the panels still generated useful power (Modi & Patel, 2024). Still, a p-value of 0.053 is close to the cut-off. Only data from several seasons can show whether the small yield gap is a real effect of shading or just variation within a single 60-day trial.

Limitations and future work

The findings should be generalised with care, for the following reasons. 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, we reported energy and yield separately and did not calculate a land equivalent ratio or a similar functional unit (Leon & Ishihara, 2018; Gosgot Angeles et al., 2026), which makes direct comparison with other agrivoltaic sites harder. Finally, we did not test reused or second-life modules, which have performed adequately in other agrivoltaic trials (Nieto-Morone et al., 2025). Because the steel frame is probably the largest cost item in Iraq, cheaper second-hand modules could make AV systems more affordable there. More field seasons covering these gaps would help those who fund or regulate agrivoltaic projects 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 CO_2e kWh^{-1}); AV-Mono was lowest at 41.80 g CO_2e 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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