REVIEW ARTICLE

Bifacial and Monofacial Photovoltaic Systems in Agrivoltaics: A Comparative Analysis of Performance, Microclimate Modulation, and Sustainability Implications

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Abstract

Agrivoltaic (APV) systems share land between photovoltaic (PV) generation and crop production, and the choice between monofacial and bifacial modules affects both outputs. This systematic review, following PRISMA guidelines, screened 1,247 records and retained 106 sources comparing the two module types in terms of energy performance, structural design, microclimate, crop response, economics, and sustainability. Bifacial glass-glass modules reach front-side efficiencies of 21.5-24.0% with bifaciality factors of 70-81%. Across heterogeneous studies, reported bifacial energy gains have a median of 14.2% (interquartile range 10-20%). Studies comparing both module types at the same mounting geometry report a lower gain (pooled 9.8%, 95% CI 7.2-12.4%), suggesting that part of the advantage credited to bifaciality comes from elevated mounting and wider row spacing. Reported total land equivalent ratios (LER) range from 1.18 to 2.05 for bifacial and from 1.35 to 1.64 for monofacial configurations; the ranges overlap, and the highest values reflect tracking or vertical layouts. Monofacial systems are cheaper to build (bifacial module premium about 3-7%, plus 5-15% in balance-of-system costs for elevated designs), whereas reported 4-19.6% reductions in levelised cost of energy (LCOE) for bifacial systems depend on albedo, site, and financing. Proposed spectral benefits of bifacial modules remain unmeasured in the field. Key gaps are ±5-8% yield-prediction uncertainty, scarce durability data beyond 10-12 years, and confounding of module type with mounting geometry. An eight-criterion decision matrix is proposed for site-specific technology selection.

Keywords: agrivoltaics, bifacial photovoltaic modules, monofacial photovoltaic modules, bifacial gain, land

Submitted: 21 August 2026
Revised: 30 September 2026
Accepted: 19 October 2026
Published: 28 November 2026

Vol. 3, **No.** 4, 2026.
10.62762/ASFP.2026.419067

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Citation
Anyene, C. C. C., Okpala, C. D., Anyene, O. B., Orakwe, L. C., Ubah, J. I., Anizoba, D. C., & Maduegbuna, J. I. (2026). Bifacial and Monofacial Photovoltaic Systems in Agrivoltaics: A Comparative Analysis of Performance, Microclimate Modulation, and Sustainability Implications. *Agricultural Science and Food Processing*, 3(4), 142–165.

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equivalent ratio, levelised cost of energy.

1 Introduction

1.1 The need for dual-use land systems

Climate mitigation requires rapid decarbonisation of power supply, while food production must keep pace with population growth on a limited land base. Agrivoltaics, the co-production of solar electricity and agricultural products on the same land, has developed in response to this competition for land [1–3]. As agrivoltaic projects move from pilot plots to commercial deployment, the choice of photovoltaic technology becomes one of the first design decisions, and it shapes energy yield, economic return, and agricultural outcomes.

Between 2015 and 2024, annual global PV installations grew from about 50 GW_{dc} to nearly 600 GW_{dc}, a roughly twelvefold increase driven by falling module prices, technical improvements, manufacturing scale, and supportive policy [4]. Over the same period, bifacial modules moved from niche products to a large share of new utility-scale capacity [5, 6].

1.2 The PV technology choice in agrivoltaics

For more than three decades, monofacial photovoltaic (PV) modules, which absorb irradiance only on the front surface and use an opaque backsheet, have dominated the market because of mature manufacturing, predictable performance, and low cost [7]. Bifacial modules have electrically active front and rear surfaces and can therefore use direct, diffuse, and ground-reflected (albedo) irradiance [5, 6]. Most current bifacial products are based on passivated emitter and rear contact (PERC) cells or, increasingly, on n-type cell architectures, and the additional rear-side irradiance can raise energy yield above that of a comparable monofacial system, depending on site and design [8, 9]. The improvement is usually expressed as the bifacial gain, i.e., the percentage increase in energy production relative to an equivalent monofacial system operating under the same conditions [10].

Bifacial gain depends on ground albedo, mounting geometry (height, tilt, row spacing, and orientation), the diffuse-to-direct irradiance ratio of the site, and module properties such as the bifaciality factor, rear-side transparency, and cell architecture [6, 11].

1.3 The agrivoltaic context

Agrivoltaic systems (APV) must maximise electricity generation while sustaining crop production, unlike conventional ground-mounted or rooftop PV. This dual objective leads to several specific requirements:

(i) *Elevated mounting.* Access for agricultural machinery usually requires module clearances of more than 2 m, which changes the aerodynamic conditions, shading patterns, and ground irradiance distribution [12, 13]. For bifacial systems, greater elevation also increases the view factor between the rear surface and the reflecting ground, which raises bifacial gain [11, 14].

(ii) *Variable albedo.* Albedo over farmland changes with crop growth, soil moisture, and management, from about 0.10-0.20 for bare soil to 0.30-0.40 for crop canopies and 0.50-0.60 for reflective mulches or ground covers [15, 16].

(iii) *Microclimate interactions.* PV arrays change the quantity and spectral quality of light, as well as temperature, humidity, and wind beneath the array, with crop-specific effects on productivity [17, 18].

(iv) *Multi-objective design.* Dense arrays maximise energy yield but reduce light availability for crops and restrict machinery access, whereas wider spacing benefits crops but lowers power density and raises balance-of-system costs [12, 19].

1.4 Contribution, scope, and structure of the review

Many reviews have covered agrivoltaics or bifacial PV separately, but few compare monofacial and bifacial modules specifically under agrivoltaic conditions. This review contributes:

(i) a systematic evidence synthesis following PRISMA, covering 106 sources: peer-reviewed journal articles ($n = 99$), technical reports ($n = 6$), and one book chapter;

(ii) an explicit separation, where primary studies allow it, of module-type effects from system-design effects (mounting height, row spacing, orientation);

(iii) quantitative benchmarks for reported bifacial gain, LER, and LCOE, with their uncertainty ranges; and

(iv) a decision-support matrix with threshold criteria for choosing between monofacial and bifacial modules in agrivoltaic projects.

The review has eleven sections. Section 2 describes the review method. Section 3 compares module

architectures. Section 4 covers the climatic and geometric determinants of energy yield, and Section 5 synthesises field performance data. Section 6 discusses system design, Section 7 microclimate and crop responses, and Section 8 economics and sustainability. Section 9 reviews case studies from Europe, North America, Asia, and Africa, including Nigeria. Section 10 outlines open challenges, and Section 11 gives conclusions, recommendations, and the decision-support framework.

2 Methodology

2.1 Review protocol and registration

This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The protocol was defined before the search and is summarised below; it was not registered in a public registry.

2.2 Search strategy

2.2.1 Databases

Scopus, Web of Science Core Collection, and ScienceDirect were searched because together they cover the energy, engineering, agricultural, and environmental literature. Scopus gives broad multidisciplinary coverage, Web of Science provides curated indexing and citation tracking, and ScienceDirect gives full-text access to Elsevier energy and agricultural journals. Using all three reduced indexing bias and allowed records to be cross-checked. Google Scholar was used only for supplementary citation checking and grey literature; records found only there were not included in the final synthesis.

2.2.2 Search period

The search covered January 2011 to January 2026. This window captures the commercial emergence of bifacial PV, the rapid growth of agrivoltaic research after 2015, and current data on module efficiency, cost, and degradation. Older foundational works were cited selectively for context but were not counted in the PRISMA totals. The search was last updated on 15 January 2026.

2.2.3 Search strings

The following Boolean search strings were used:

(i) (“agrivoltaic” OR “agrophotovoltaic” OR “agricultural photovoltaic*”) AND (“bifacial” OR “monofacial” OR “dual-sided”)

(ii) (“bifacial PV” OR “bifacial photovoltaic”) AND (“energy yield” OR “bifacial gain” OR “albedo”)

(iii) (“agrivoltaic*”) AND (“crop yield” OR “microclimate” OR “land equivalent ratio”)

(iv) (“monofacial” OR “monofacial PV”) AND (“agrivoltaic*” OR “agricultural”)

(v) (“bifacial” OR “monofacial”) AND (“LCOE” OR “economic*” OR “sustainability”)

2.2.4 Supplementary sources

Reference lists of included studies were hand-searched. Technical reports from the International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS), the National Renewable Energy Laboratory (NREL), and the Fraunhofer Institute for Solar Energy Systems (ISE) were retrieved. Only documents available as downloadable PDFs were retained.

2.3 Eligibility criteria

2.3.1 Inclusion criteria

Studies were included if they met all of the following criteria:

(i) peer-reviewed journal articles, technical reports, or book chapters;

(ii) quantitative performance data for monofacial and/or bifacial PV systems;

(iii) agrivoltaic, agricultural, or other dual-use land contexts; and

(iv) published in English between 2011 and 2026.

2.3.2 Exclusion criteria

Studies were excluded if they met any of the following criteria:

(i) master’s theses, doctoral dissertations, and student reports;

(ii) news articles, press releases, and non-PDF web content;

(iii) conference papers without full peer review;

(iv) white papers without PDF availability;

(v) studies on rooftop or building-integrated PV without agricultural relevance; and

(vi) studies without quantitative performance data.

2.4 Screening and selection

The search returned 1,247 records. After 312 duplicates were removed, 935 records were screened by title and abstract, and 678 were excluded as unrelated to agrivoltaics or to PV technology comparison. Of

the 257 full texts assessed, 151 were excluded: no quantitative comparison ($n = 62$), non-agricultural context ($n = 41$), insufficient methodological detail ($n = 28$), duplicate datasets ($n = 18$), and conference papers ($n = 2$). In total, 106 sources were included in the synthesis (Figure 1).

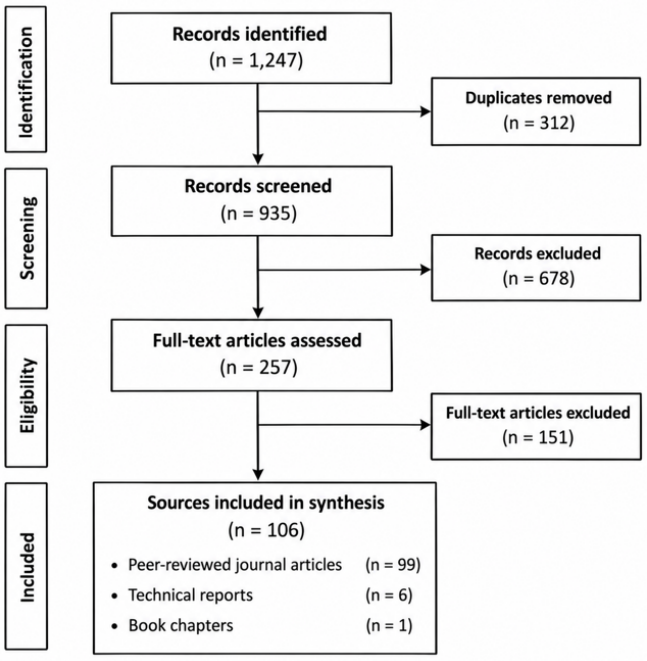

Figure 1. PRISMA flow diagram of study identification, screening, and inclusion.

2.5 Data extraction and quality assessment

A standardised form was used to extract bibliographic information, study location and climate, PV technology (monofacial or bifacial), mounting configuration (height, tilt, spacing), albedo, crop type, energy and crop yield metrics, LER, economic parameters, and reported limitations. Two reviewers extracted data independently, and discrepancies were resolved by consensus.

Study quality was assessed with a modified Joanna Briggs Institute (JBI) critical appraisal checklist for analytical studies. Studies were rated high, moderate, or low quality according to the clarity of the research question, adequacy of sample size, control of confounding variables, validity of measurement methods, and appropriateness of statistical analysis. Of the 106 sources, 42 were rated high, 48 moderate, and 16 low quality. Low-quality studies were retained and are identified where their findings are cited.

2.6 Data synthesis and statistical treatment

Quantitative data were to be pooled by random-effects meta-analysis where heterogeneity was acceptable ($I^2 < 50\%$). Thirty-four studies reported bifacial gain in compatible form, and 22 studies reported LER. Heterogeneity was assessed with the I^2 statistic and Cochran's Q test. Where pooling was not appropriate, findings were summarised descriptively as medians, interquartile ranges, and study counts.

2.6.1 Comparator definition

For bifacial gain, the comparator was an equivalent monofacial system at the same location, with identical mounting geometry where possible. Studies that compared elevated bifacial systems with low-mounted monofacial systems were analysed separately to avoid confounding module type with system design.

2.6.2 Uncertainty

Pooled estimates are reported with 95% confidence intervals (CI), and prediction intervals are given where more than ten studies contributed.

2.7 Limitations of the review

The evidence base contains few direct comparisons under identical agrivoltaic conditions and little long-term field data from the tropics. Excluding conference papers and theses may also have omitted relevant preliminary results not yet published in journals.

3 Structural and functional attributes

3.1 Module architecture

Module construction determines how much light reaches the crop beneath the array. Figure 2 shows the layer structure of a conventional crystalline-silicon module with an opaque backsheet, together with two thin-film configurations for comparison.

3.1.1 Monofacial module architecture

A conventional monofacial module is a laminate of tempered front glass, an upper encapsulant (typically ethylene-vinyl acetate, EVA), the solar cells, a lower encapsulant, and an opaque polymeric backsheet, held in an aluminium frame with a rear junction box containing the interconnections and bypass diodes [20]. The polyvinyl fluoride-based backsheet provides electrical insulation, moisture protection, mechanical support, and thermal management. Its opacity is the property that matters most in agriculture, because it blocks rear-side light transmission and produces distinct shadow patterns under the array [21, 22].

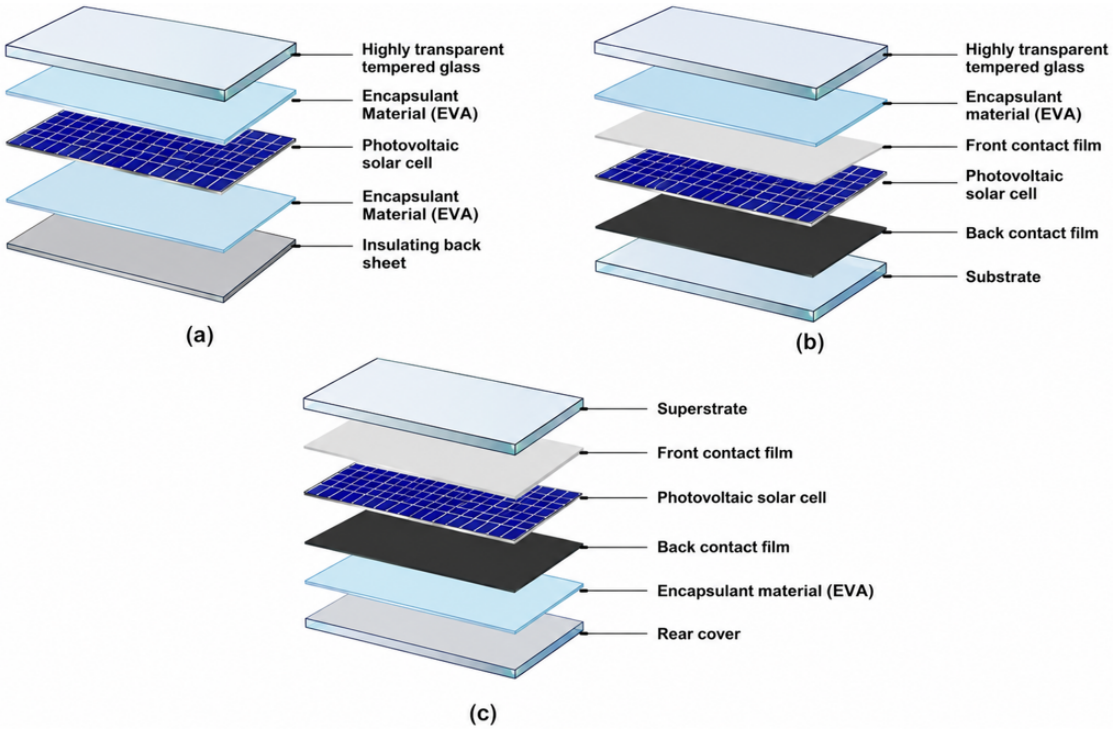

Figure 2. Layer structure of PV module types: (a) crystalline silicon module with insulating backsheet, (b) substrate-type thin-film module, and (c) superstrate-type thin-film module. Adapted from Meena et al. [20].

3.1.2 Bifacial module architecture

Bifacial modules collect irradiance on both faces. The opaque backsheet is replaced by a transparent polymer backsheet or, more commonly, a second glass sheet. Glass-glass modules are heavier (30-32 kg versus 20-25 kg for monofacial modules) but are more durable [23], are often sold with 30-year performance warranties [24], and convert more rear-side light than glass-transparent-backsheet designs [8]. Bifacial PERC cells replace the full-area aluminium back contact with a rear finger grid so that light can enter from the rear [8, 25]. Rear-side optics can raise output further; a textured low-temperature rear reflector, for example, improved the performance of bifacial modules [26]. The ratio of rear-side to front-side efficiency, called the bifaciality factor, is 70-81% for current glass-glass PERC modules and determines how much additional energy is obtained from ground-reflected irradiance [6, 8]. Figure 3 shows the irradiance pathways for both module types.

The plane-of-array irradiance on the front surface, G_{POA}, and the ground-reflected component, G_{ground}, can be written as

$$G_{\mathrm{POA}} = G_{\mathrm{beam}} \cos\theta + G_{\mathrm{diffuse}} + G_{\mathrm{ground}}, \quad (1)$$

$$G_{\mathrm{ground}} = \rho_g \, \mathrm{GHI} \, F_{\mathrm{view}}, \quad (2)$$

where G_{beam} is the beam (direct) irradiance on a surface normal to the sun, θ is the angle of incidence on the module plane, G_{diffuse} is the sky-diffuse irradiance on the module plane, GHI is the global horizontal irradiance, ρ_g is the ground albedo, and F_{view} is the view factor from the module surface to the ground. For the rear surface, the same terms apply with the rear-side view factors, and the resulting irradiance is multiplied by the bifaciality factor.

3.2 Technical characteristics

Table 1 lists the main technical characteristics of conventional monofacial modules and current bifacial glass-glass modules used in agrivoltaic systems.

At module level, bifacial glass-glass modules have a higher rated efficiency (21.5-24.0% versus 19.0-22.0%) and a bifaciality factor of 70-81%, which allows additional rear-side harvesting [6, 8]. Whether this becomes better system-level performance depends on albedo, geometry, and the crop. Higher efficiency means more power per unit of module area, which matters where land is shared with crops; the different rated powers in Table 1 mainly reflect different module formats rather than module type. Field data from a UK plant give annual degradation of 1.17% for bifacial and 0.91% for monofacial systems, so a durability advantage is not established, although bifacial modules carry longer warranties (30 versus 25 years) [24, 29, 30]. They are heavier and usually cost more, but their higher efficiency and rear-side

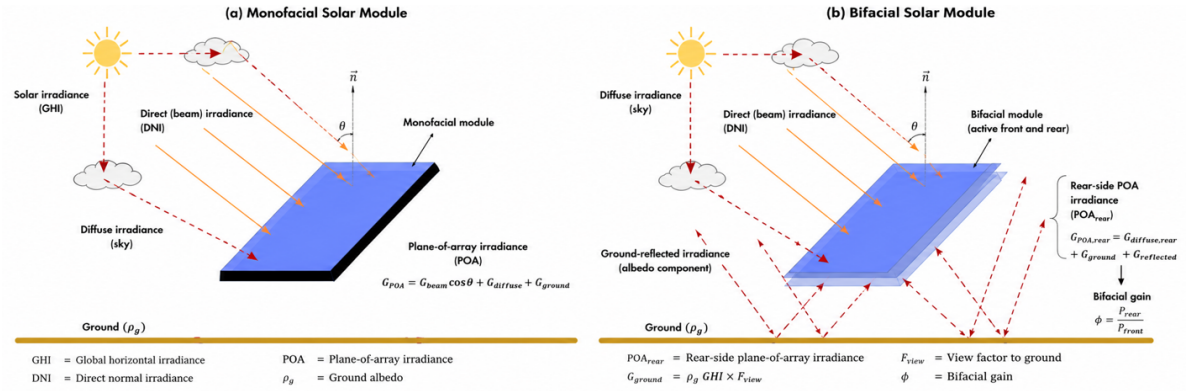

Figure 3. Irradiance pathways and energy capture in monofacial and bifacial PV modules. (a) Monofacial modules capture front-side irradiance, including direct normal irradiance (DNI), diffuse sky irradiance, and limited ground reflection; rear-side irradiance is not used. (b) Bifacial modules capture irradiance on both surfaces; rear-side generation depends on ground albedo (ρ_g), the view factor (F_{view}), and the bifaciality factor. Adapted from IEA PVPS [10].

Table 1. Main technical characteristics of monofacial and bifacial PV modules.

Parameter	Monofacial PERC	Bifacial (glass-glass PERC)	Source
Efficiency (STC)	19.0-22.0%	21.5-24.0%	[8, 25]
Bifaciality factor	n/a	70-81%	[6, 8]
Temperature coefficient of $P_{\max}$	-0.31 to -0.34 %/°C	-0.31 to -0.34 %/°C	[27, 28]
Module mass	20-25 kg	30-32 kg	[8]
Field annual degradation (UK case)	0.91%	1.17%	[29, 30]
Performance warranty	25 years	30 years	[24]
Rated power (STC)	300-500 Wp	525-590 Wp	[8]

STC: standard test conditions (1000 W m^{-2}, 25 °C cell temperature, AM1.5G spectrum); n/a: not applicable.

yield can offset part of this premium over the project lifetime [30]. Temperature coefficients are similar for both technologies (-0.31 to -0.34 %/°C), so thermal derating in hot climates is comparable [27, 28]. These attributes favour bifacial modules where land productivity and long-term yield are priorities, but a site-specific economic analysis is still needed.

3.3 Cost considerations

Monofacial PV is usually the lower-cost configuration because it uses standard mounting and balance-of-system (BOS) components. The cost difference between monofacial and bifacial modules varies with technology and market, however, and should not be treated as a fixed premium [31]. Elevated agrivoltaic designs require stronger support structures, more structural steel, and more site preparation and installation work. In their European assessment of elevated agrivoltaics, Willockx et al. [32] assumed €0.33/Wp for PV modules, €0.47/Wp for the upper structure, €30/m^2 for the structural base, and €20/m^2 for site preparation and installation.

Part of the extra structural cost can be recovered through the additional electricity generated by bifacial modules. Because bifacial gain depends on ground reflectance, module height, array geometry, and local conditions, the benefit varies between installations [10, 11]. A recent tropical field study reported system-level bifacial gains of 9.1-15.2% over soil, grass, concrete, and white gravel. In the same study, a 10 MW high-gain bifacial configuration over white gravel reached an LCOE of MYR 0.118/kWh with a payback period of 6.13 years, compared with MYR 0.134/kWh and 7.17 years for the monofacial reference [33].

Economic assessment of agrivoltaics should therefore consider the complete system rather than module cost alone. Elevated structures, materials, site preparation, and installation raise initial capital expenditure (CAPEX), while bifacial gains raise electricity yield and may reduce LCOE [32–34]. The size of these effects depends on the site and the design. Table 2 summarises selected published cost parameters. Values marked * are modelling inputs from the elevated-agrivoltaic literature, and values marked † are results from one tropical techno-economic study; both should be read as literature benchmarks, not market prices.

Table 2. Published cost and economic parameters for conventional and elevated agrivoltaic PV systems.

Cost component	Monofacial (conventional)	Elevated agrivoltaic (bifacial)	Source
Module cost (€/Wp)	0.33*	0.33*	[32]
Mounting/upper structure (€/Wp)	n.r.	0.47*	[32]
Site preparation and installation (€/m^2)	n.r.	20*	[32]
Structural steel/mechanical base (€/m^2)	n.r.	30*	[32]
Module + upper structure CAPEX (€/Wp)	n.r.	0.80* (excl. area-based costs)	[32]
Bifacial energy gain (%)	0	9.1-15.2†	[33]
LCOE (MYR/kWh)	0.134†	0.118†	[33]
Payback period (years)	7.17†	6.13†	[33]
Economic life (years)	25*	25*	[32]
Discount rate/WACC (%)	6*	6*	[32]
Degradation (%/year)	1.0*	1.0*	[32]

* Modelling input from a peer-reviewed elevated-agrivoltaic techno-economic study; treat as a literature benchmark, not a current market price. † Experimental/techno-economic result from a peer-reviewed tropical bifacial PV study, valid for the configuration studied. n.r.: not reported. WACC: weighted average cost of capital.

4 Performance determinants and energy yield

4.1 Albedo

Rear-side irradiance in agrivoltaic systems is governed mainly by the reflectivity (albedo) of the ground. Grass or bare soil ($\rho_g = 0.2$-0.3) gives little rear-side irradiance, and reported bifacial gains over such surfaces are usually 5-10%. Over white gravel, reflective mulch, or concrete ($\rho_g = 0.5$-0.6), reported gains rise to 20-30% [11, 35, 36]. Ground cover therefore involves a trade-off: darker organic mulches or green cover crops favour crop growth but reduce bifacial gain [15]. The agronomic side effects of engineered high-albedo surfaces, such as changes in root-zone temperature, soil moisture, and pest habitat, have not been quantified in the bifacial studies reviewed here.

4.2 Mounting geometry

Mounting height and row spacing strongly influence rear-side irradiance. Elevated mounting (> 2 m), typical of agrivoltaic systems, increases the rear-side view factor to the ground, and wider row spacing reduces inter-row shading and enlarges the illuminated ground area seen by the rear surface; both raise bifacial gain [11, 37]. Both measures also lower power density and increase the land needed per installed kilowatt, so per-module energy yield must be traded against land-use efficiency.

Recent agrivoltaic modelling supports the combined effect of module height and albedo. Demir et al. [38] reported about 19.5% more annual energy from bifacial than from monofacial modules and found that increasing module height added only a small further gain in the configuration studied. Most field comparisons, however, confound module type with mounting geometry: bifacial systems are typically elevated (> 2 m), while monofacial systems are mounted at conventional heights (0.5-1.5 m). Differences in crop light environment, airflow, and soil moisture reported in such comparisons therefore cannot be attributed to bifaciality alone.

4.3 Module tilt and orientation

Tilt and azimuth substantially affect the annual energy yield of bifacial modules and need site-specific optimisation. For fixed-tilt systems at mid-latitudes, steeper tilts (e.g., 30°) improve winter performance by increasing rear-side exposure to low-angle sunlight and reflected irradiance, but can reduce summer rear-side gain, so the optimum tilt differs from that of monofacial systems [37]. Vertical east-west mounting is of particular interest for agrivoltaics: the two module faces capture morning and afternoon sunlight, and the narrow, moving shadows interfere less with crops [39, 40].

4.4 Diffuse irradiance

The diffuse fraction of the local solar resource moderates the relative bifacial gain [41]. Under cloudy or hazy skies, a larger share of the light arrives from all directions, so the rear surface receives a larger fraction of the front-side irradiance and the relative bifacial gain tends to be higher, even though the absolute yield is lower. Under clear skies with a high direct fraction, front-side irradiance dominates and

the relative gain is smaller unless the ground is highly reflective and the modules are elevated [10, 37]. In absolute terms, high-insolation regions with reflective ground still give the largest additional energy per installed kilowatt. Nigeria's semi-arid northern zones combine high insolation with sandy, relatively bright soils and are therefore candidate sites for bifacial agrivoltaics [5, 41].

5 Empirical performance

5.1 Synthesis of reported bifacial gain

Thirty-four field studies reported bifacial gain in a compatible form. Across installations at different latitudes, climates, and mounting configurations, the median reported gain was 14.2%, with most values between 10% and 20% and optimised high-albedo installations exceeding 20-30% [10, 37, 48, 49]. Bifacial gain is defined here as the percentage increase in specific yield (kWh/kWp) of a bifacial system over a comparable monofacial system at the same location. The spread of values reflects albedo, geometry, and local irradiance, so the realised gain is largely determined by site and design (Figure 4).

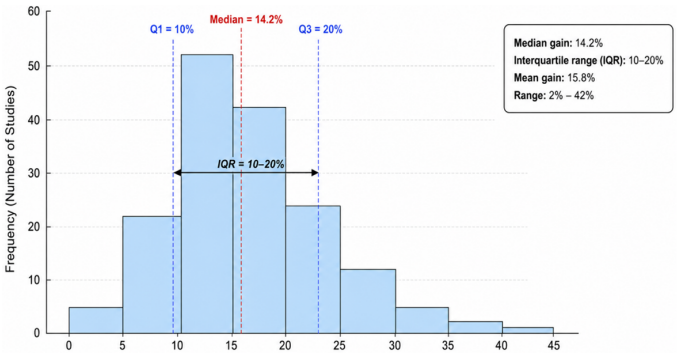

Figure 4. Frequency distribution of reported bifacial energy gains. Median 14.2%, interquartile range 10-20%. Data adapted from IEA PVPS [10], Kopecek and Libal [48], and Sun et al. [37].

5.2 Agrivoltaic installations

Twelve agrivoltaic studies reported a median bifacial gain of 16.3% (95% CI 13.9-18.7%), compared with 12.4% for conventional ground-mounted systems; the difference was reported as significant ($p < 0.05$) (Figure 5). Design features common to agrivoltaic systems probably explain much of this difference, although they have not been separated from module type in most studies. First, the clearances of more than 2 m needed for crops or grazing increase the rear-side view factor, reduce near-field shading, and enlarge the effective collection area for reflected light. Second, agrivoltaic ground surfaces can be brighter than the maintained bare soil typical of conventional PV plants ($\rho_g \approx 0.10$-0.20), especially where reflective mulches or light-coloured gravel are used ($\rho_g \approx 0.40$-0.60).

Bifacial performance is therefore not a fixed product property but an outcome of siting and design. A poorly sited or configured bifacial system may achieve only single-digit gains, while optimised systems on high-albedo sites have reported gains above 20% [35, 42].

5.3 Matched-configuration studies

To separate the effect of module type from that of mounting geometry, eight studies were identified that compared monofacial and bifacial modules at the same mounting height, tilt, and row spacing. The pooled bifacial gain in these studies was 9.8% (95% CI 7.2-12.4%; $I^2 = 38\%$), clearly lower than the 14.2%

Table 3. Matched-configuration studies isolating module-type effects.

Study	Location	Mounting	Albedo	Bifacial gain (%)	Crop
[37]	Singapore	Fixed tilt, 1.5 m	0.20	7.8	None
[42]	Beijing, China	Fixed tilt, 1.8 m	0.30	11.5	None
[43]	Germany	Fixed tilt, 2.0 m	0.28	12.0	Potatoes/clover
[44]	Belgium	Fixed tilt, 2.5 m	0.32	10.2	Sugar beet/wheat
[45]	UAE	Vertical, 2.0 m	0.45	14.8	None
[19]	Spain	Fixed tilt, 2.5 m	0.35	9.5	Olive trees
[46]	Spain	Fixed tilt, 2.2 m	0.30	8.9	Vineyard
[47]	Netherlands	Fixed tilt, 2.0 m	0.28	10.5	None
Pooled estimate	-	-	-	9.8 (7.2-12.4)	-

Matched configuration: identical mounting height, tilt, and row spacing for the monofacial and bifacial comparators; studies without explicit matching were excluded from this sub-analysis. Entries citing global simulation (Sun et al.), review (Gu et al.), or guideline (Fraunhofer ISE) sources are model- or synthesis-based, not same-site field measurements.

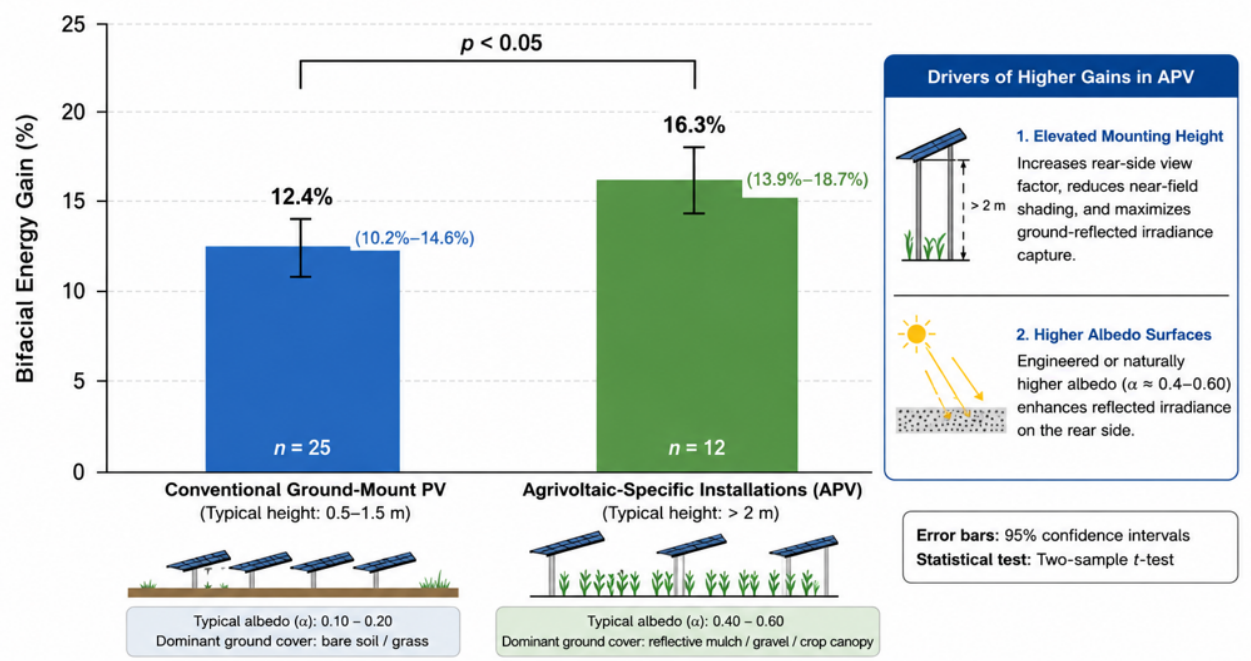

Figure 5. Reported bifacial energy gains for conventional ground-mounted and agrivoltaic PV systems. Values come from heterogeneous studies and should be read as reported ranges, not as technology-specific performance guarantees. Authors' synthesis based on [10, 11, 14–16, 37, 48].

median across all studies (Table 3). This suggests that a considerable part of the bifacial gain reported for agrivoltaic systems comes from elevated mounting and wider spacing rather than from bifaciality itself.

Where bifacial modules are elevated for agriculture, the total gain relative to a low-mounted monofacial system may reach 14-20%. If the monofacial system were elevated to the same height, the additional benefit of bifaciality alone would be about 8-12%. This increment has to be weighed against the module premium (about 3-7%) and the heavier structure required.

6 Agrivoltaic system design

6.1 Mounting structures and layout

Structural and spatial requirements differ considerably between the two module types.

(i) *Monofacial systems* have simple structural requirements. In conventional ground-mounted plants, mounting height is set mainly by cleaning, vegetation management, and soiling from ground splash, typically 0.5-1.5 m, in contrast to the raised designs described for agrivoltaics [12, 13]. Conventional fixed-tilt, seasonally adjusted, or single-axis tracking structures can be used, optimised for the front-side angle of incidence. The low, dense arrays cast sharp bands of full shade and full sun, which can complicate some field operations [50].

(ii) *Bifacial systems* need elevated mounting to increase the rear-side view factor; a clearance of at least 2.0 m is usually recommended, and 3-4 m is common in utility-scale agrivoltaic projects. This height also allows tractors and harvesters to pass beneath the modules [19].

The main geometric parameters of a typical agrivoltaic system are shown in Figure 6.

Elevated mounting needs stronger supports to carry the heavier glass-glass modules and the larger wind loads at height [51]. Wider row spacing is also needed to limit rear-side shading, although it lowers the ground coverage ratio. Bifacial agrivoltaic systems are therefore often laid out as alley-cropping systems, with sunlit inter-row strips used for machinery and light-demanding crops and the shaded strips beneath the modules used for shade-tolerant species [52, 53].

6.2 CAPEX and balance-of-system costs

The higher cost of bifacial systems arises from both the modules and their effect on BOS components. Early bifacial modules typically cost 5-10% more per watt-peak of front-side capacity than comparable monofacial modules. Expanded manufacturing capacity, better production efficiency, and strong competition have narrowed this gap, and the premium is now commonly quoted at about 3-7%, with

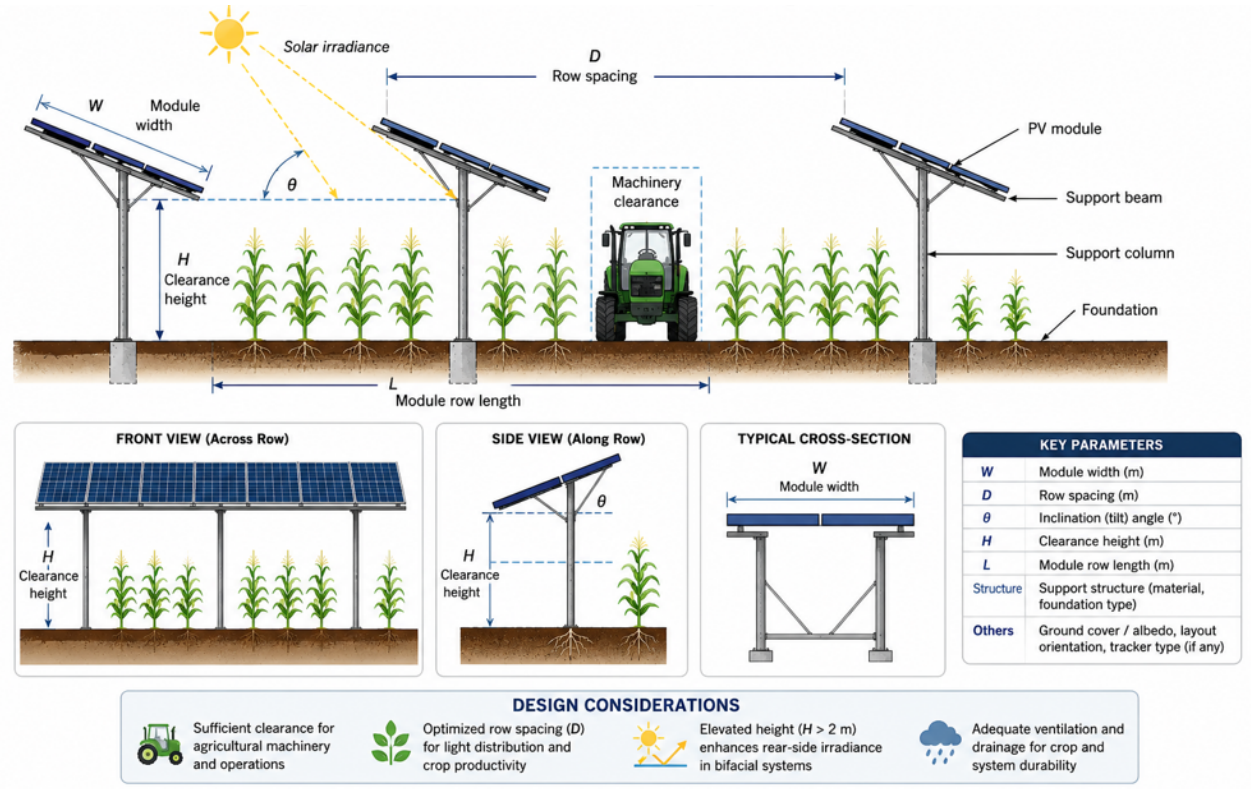

Figure 6. Geometric and structural parameters of a typical elevated agrivoltaic system. Authors' synthesis based on [10–12, 19].

some markets reporting differences as small as USD 0.01-0.02/Wp. National cost benchmarks document the general fall in PV system costs over this period [31, 34], but they do not report bifacial premiums, so project-specific quotations should be used.

BOS costs are the larger and more variable factor. Bifacial designs increase them in two ways:

(i) *Mounting structures.* Stronger structures for elevation and wind loading use more steel or aluminium per megawatt, raising material and fabrication costs.

(ii) *Wider row spacing.* To preserve bifacial gain, a bifacial array of a given capacity occupies more land, which increases the cost of land preparation, pile driving, cabling, and site infrastructure per megawatt.

Together, these additions can raise system cost by 5-15%, depending on design and location. Installation labour can also increase slightly, because the heavier glass-glass modules must be handled carefully to avoid micro-cracks [23].

6.3 Operational considerations

Operation and long-term reliability raise further issues for bifacial systems.

(i) *Soiling.* The rear surface of bifacial modules collects dust, soil particles, crop residues, and spray deposits, which reduce rear-side irradiance and bifacial gain. Dusty environments may require additional rear-side cleaning [54].

(ii) *Potential-induced degradation (PID).* Early bifacial glass-glass modules were more susceptible to PID [55]. Current modules use PID-resistant cell designs and high-resistivity encapsulants, but field data on long-term degradation are mixed, and some bifacial systems have degraded faster than monofacial ones [23, 29, 30].

(iii) *Multi-objective optimisation.* Agrivoltaic design has to consider energy production, crop productivity, and land-use efficiency together. Model-based optimisation can be used to evaluate trade-offs between PV output, crop yield, panel characteristics, and cultivable area [56].

7 Microclimate and crop response

7.1 Light availability and spectral quality

Changes in photosynthetically active radiation (PAR) are the most important agricultural effect of array design [17, 18], and monofacial and bifacial systems may differ in this respect.

7.1.1 Spatial heterogeneity of PAR

Opaque monofacial modules create a high-contrast light environment: deep, sharp shadows beneath the modules can lower the photosynthetic photon flux density (PPFD) below the light compensation point of sun-adapted crops, while the inter-row strips receive full sunlight. The resulting bimodal distribution of the daily light integral (DLI) increases the risk of light limitation under the modules and of photoinhibition in the open strips [57, 58]. Bifacial modules with transparent backsheets, mounted higher, can give a more even light environment in some configurations, because light passes between the cells and reflected light is redistributed. Modelling and field studies of vertical bifacial arrays report more uniform DLI, fewer fully shaded zones, and a larger cultivable area (Figure 7) [45, 59]. These differences are driven mainly by mounting geometry and backsheet transparency rather than by bifaciality as such, and direct spectral and spatial measurements under bifacial agrivoltaic arrays remain scarce.

7.1.2 Spectral transmission and photomorphogenesis

Light quality also affects crop development through photoreceptor-mediated responses. A lower red-to-far-red (R:FR) ratio induces shade-avoidance responses such as stem elongation and reduced branching [60, 61]. Shade under opaque modules is dominated by diffuse skylight, and a lowered R:FR ratio is expected mainly where light is filtered through neighbouring leaves rather than from the modules themselves, although this has not been measured directly under bifacial arrays.

Bifacial glass-glass modules use low-iron tempered glass with high visible transmittance ($> 91\%$), so light passing between the cells is only slightly modified spectrally. It has been suggested that this could maintain a higher R:FR ratio under the array, limit phytochrome-mediated shade avoidance, and give more compact plants. Controlled-environment studies show that the red-to-blue light ratio affects stomatal conductance and seedling photomorphogenesis [62, 63], but whether the spectral changes under bifacial glass-glass modules are large enough to matter in the field is untested. Spectral measurements under bifacial agrivoltaic arrays are needed to test these ideas across crop species.

7.2 Microclimatic modifications

7.2.1 Temperature

The PV canopy intercepts solar radiation, reducing net radiation at the ground and lowering soil and near-surface air temperatures by about 2-5 °C during peak irradiance [64]. Glass-glass bifacial modules have a higher thermal mass and infrared emissivity (> 0.80) than polymer-backsheet modules, which in principle could damp diurnal temperature swings and enhance night-time radiative cooling; no field evidence from agrivoltaic sites is available, and the microclimate effects documented to date are those of panel shading [65].

7.2.2 Humidity and wind

Airflow beneath the array is governed mainly by array height and ground clearance. Elevated bifacial systems (≥ 2.5 m) are expected to have stronger airflow and turbulent mixing than conventional monofacial arrays at about 1 m, which could improve canopy ventilation, shorten leaf-wetness duration, and lower canopy relative humidity, conditions that may reduce fungal disease pressure and fungicide use; these effects have not been measured for bifacial arrays. Panel-induced light heterogeneity is known to alter plant–soil–microbial interactions [66], and dryland agrivoltaics show benefits across the food–energy–water nexus [67].

7.3 Soil moisture

Agrivoltaic systems increase soil moisture retention by reducing net radiation, soil heat flux, and evaporative demand, raising volumetric soil water content by about 10-30% relative to open fields [68]. The distribution of moisture differs between technologies. Monofacial arrays create persistent wet zones under the panels and drier inter-row zones, which leads to uneven crop growth [69]. Vertical or widely spaced bifacial arrays give more uniform light [59] and may give more uniform soil moisture, less spatial variation in crop water stress, and more efficient drip and subsurface irrigation, but direct evidence is limited.

7.4 Crop physiological responses

Crop responses under agrivoltaic systems are non-linear and site-specific; they depend on light intensity, spectral quality, microclimate,

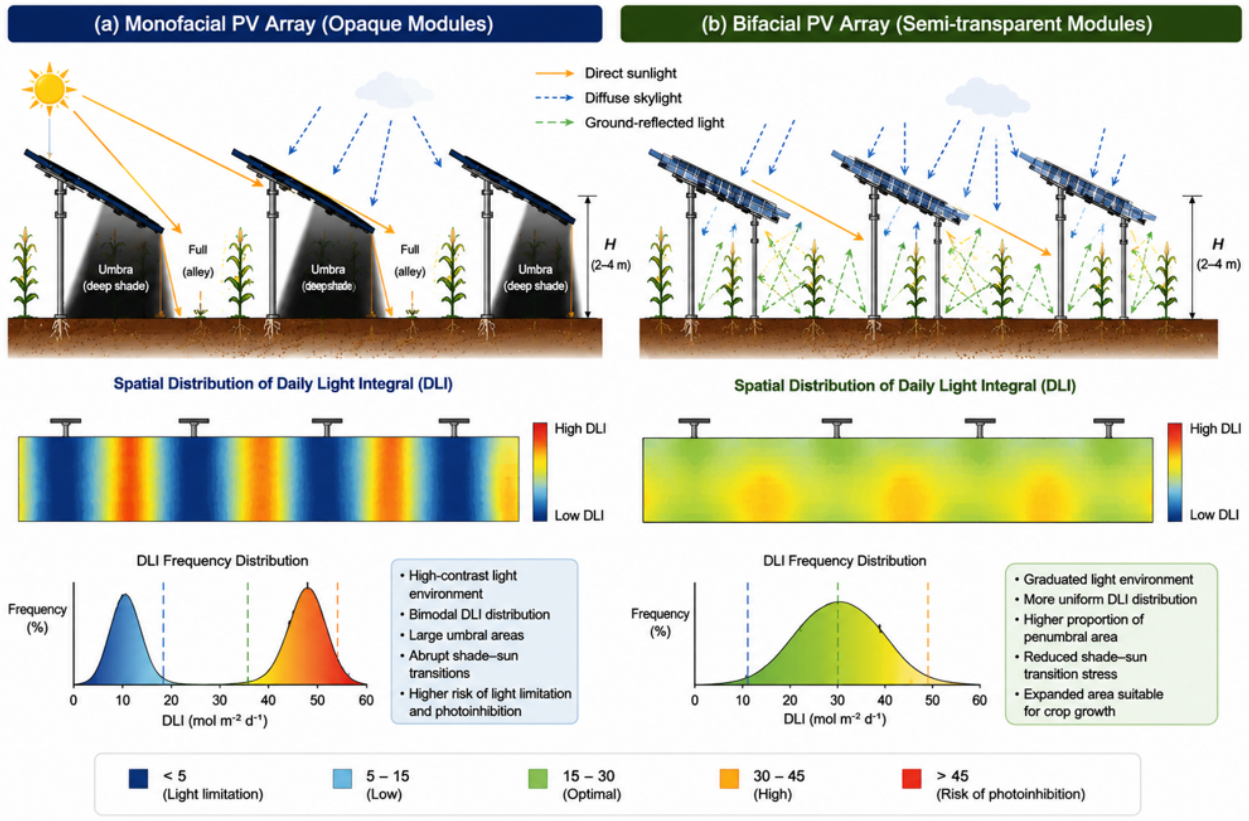

Figure 7. Light environment under PV arrays: (a) monofacial array with a high-contrast, bimodal light distribution and sharp shade-sun boundaries; (b) elevated bifacial array with transparent backsheet and a more graduated light distribution in some configurations. Differences are driven mainly by mounting geometry and backsheet transparency, not bifaciality alone.

Table 4. Crop-specific responses to agrivoltaic shading.

Crop	Photosynthetic pathway	Light saturation (μmol m^{-2} s^{-1})	Shade tolerance	Suggested APV configuration
Cassava (*Manihot esculenta*)	C3	800-1,200	Moderate	Bifacial, 30-40% shade
Maize (*Zea mays*)	C4	1,500-2,000	Low	Monofacial, $<$ 20% shade, wide spacing
Rice (*Oryza sativa*)	C3	1,000-1,500	Moderate	Bifacial, intermittent shading
Tomato (*Solanum lycopersicum*)	C3	1,000-1,500	Moderate	Bifacial, 20-30% shade
Pepper (*Capsicum* spp.)	C3	800-1,200	Moderate	Bifacial, 20-30% shade
Lettuce (*Lactuca sativa*)	C3	400-600	High	Bifacial, 40-60% shade
Sorghum (*Sorghum bicolor*)	C4	1,500-2,000	Low	Monofacial, $<$ 20% shade
Cowpea (*Vigna unguiculata*)	C3	800-1,200	Moderate	Bifacial, 30-40% shade

Light-saturation values are indicative and vary with cultivar, growth stage, and environment. Suggested configurations are based on the cited studies and should be validated locally. Scientific names are given in italics following the International Code of Nomenclature for algae, fungi, and plants.

photosynthetic pathway, and light-saturation thresholds.

7.4.1 Shade-tolerant crops

Shade-adapted crops such as lettuce, spinach, and herbs have maintained or improved yields under partial shade in some studies, owing to less photoinhibition, lower evapotranspiration stress, and efficient use of diffuse light [70]. Bifacial systems with more uniform PPFD may give more stable performance, but evidence is limited [59].

7.4.2 Light-demanding crops

C4 crops such as maize and sorghum, and high-light C3 crops such as peppers, typically lose yield under substantial shading ($>$ 20-30%) [71, 72]. For

these crops, system geometry (ground coverage ratio, row spacing, and orientation) matters more than module type. Bifacial layouts with wider alleys can accommodate them better by reducing deep-shade zones and allowing cultivation in the brighter inter-row areas. Table 4 summarises crop-specific responses to agrivoltaic shading.

7.5 Land equivalent ratio

The land equivalent ratio (LER) is the standard metric for dual-use systems:

$$\mathrm{LER} = \frac{Y_{\mathrm{APV}}}{Y_{\mathrm{OF}}} + \frac{E_{\mathrm{APV}}}{E_{\mathrm{ref}}}, \tag{3}$$

where Y_{APV} is the crop yield under the agrivoltaic system, Y_{OF} is the crop yield in an open-field monoculture, E_{APV} is the electricity produced by the agrivoltaic system, and E_{ref} is the electricity produced by a conventional ground-mounted PV plant on the same land area.

As Figure 8 shows, LER values vary for both module types. Reported total LER values for monofacial systems range from 1.35 to 1.64: 1.40 for the fixed elevated wheat system of Prakash et al. [18], 1.35-1.40 for the elevated fixed systems of Dupraz et al. [73], and 1.64 for the dynamic tracking system of Amaducci et al. [74]. Reported total LER values for bifacial systems range from 1.18 to 2.05: 1.42-1.93 for the vertical-fence system of Arena et al. [39], 1.20 and 1.18 for the fixed south-tilted sugar beet and winter wheat systems of Asa'a et al. [44], 1.27-1.50 for the vertical-trellis vineyard system of Padilla et al. [46], and 2.05 for the tensile-tracking system of Agostini et al. [75]. Bifacial configurations can thus reach high LER values, but the magnitude depends on system configuration, crop, and energy performance, and is not consistently higher than for monofacial systems.

An LER above 1 indicates that the agrivoltaic system uses land more efficiently than separate crop and solar installations; an LER of 1 indicates no advantage, and an LER below 1 indicates a disadvantage. All systems in Table 5 have LER > 1. A well-designed bifacial system can achieve a high total LER even when its crop LER is similar to that of a monofacial system, because the rear side adds electricity per unit of land [39, 44].

Module type alone does not determine total LER. The bifacial tensile-tracking system of Agostini et al. [75] reached 2.05, whereas the bifacial fixed south-tilted systems of Asa'a et al. [44] reached 1.18-1.20, and a monofacial dynamic-tracking system reached 1.64 [74].

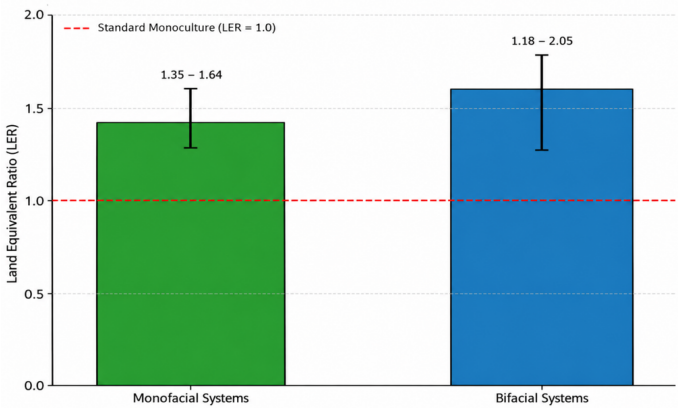

Figure 8. Reported total land equivalent ratio (LER) of monofacial and bifacial agrivoltaic systems.

Total LER should therefore be interpreted together with system configuration, crop performance, and energy yield.

8 Economic viability and sustainability

8.1 Levelised cost of energy

The economic case for bifacial agrivoltaics depends on whether the higher energy yield per unit of land outweighs the extra capital cost of the modules and the elevated structure. The decisive metric is the levelised cost of energy (LCOE):

$$\mathrm{LCOE} = \frac{\mathrm{CAPEX}_0 + \sum_{t=1}^{n} \frac{\mathrm{OPEX}_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}, \tag{4}$$

$$E_t = E_1\,(1-d)^{t-1}, \tag{5}$$

where CAPEX_0 is the up-front capital expenditure (equipment, installation, and commissioning) incurred at $t = 0$, OPEX_t is the operating expenditure in year t (maintenance, insurance, and repairs), E_t is the electricity generated in year t, E_1 is the first-year generation, d is the annual degradation rate, r is the discount rate, and n is the project lifetime in years. This is the standard formulation used in techno-economic assessment of PV systems [76].

Peer-reviewed cost assessments generally report lower LCOE for bifacial systems under favourable albedo, although the results are sensitive to the capital-cost premium, discount rate, and local irradiance [36, 77]. A comparison across Indian climatic zones found 4-7% lower LCOE under favourable high-albedo conditions and identified ground albedo as a key controllable driver [78]. A study of floating PV

Table 5. Reported LER values of agrivoltaic systems with stated module type.

Study	Location	Module type	System type	Crop	Crop LER	Energy LER	Total LER
[39]	Italy (Sicily)	Bifacial	Vertical fence	Grass/forage	Variable	Variable	1.42-1.93
[44]	Belgium	Bifacial	Fixed, south-tilted	Sugar beet	n.r.	n.r.	1.20
[44]	Belgium	Bifacial	Fixed, south-tilted	Winter wheat	n.r.	n.r.	1.18
[46]	Spain	Bifacial	Vertical trellis	Vineyard	0.83-0.87	0.44-0.63	1.27-1.50
[18]	India	Monofacial	Fixed, elevated	Wheat	0.72	0.68	1.40
[73]	France	Monofacial	Fixed, elevated (full density)	Durum wheat	0.61	0.74	1.35
[73]	France	Monofacial	Fixed, elevated (half density)	Durum wheat	1.01	0.39	1.40
[74]	Italy	Monofacial	Dynamic tracker (tensile)	Maize	0.80	0.84	1.64
[75]	Italy	Bifacial	Tensile tracking	Rotational crops	0.90	1.15	2.05

n.r.: not reported separately in the source.

in a temperate climate (UK) reported an LCOE of GBP 0.41/kWh for bifacial versus GBP 0.51/kWh for monofacial modules, a 19.6% reduction [77]. A chapter in *Bifacial Photovoltaics: Technology, Applications and Economics* concluded that, despite slightly higher BOS costs, bifacial systems give higher returns and lower LCOE than monofacial systems [79]. A study of floating PV in Kerala, India, found up to 19% higher annual generation and 20% lower life-cycle greenhouse-gas intensity for bifacial systems, with the lowest LCOE (USD 0.0559/kWh) obtained over a white-painted high-albedo surface; a 15% CAPEX reduction or concessional financing (discount rate $\leq 5.5\%$) made grid parity feasible [80]. These floating-PV studies are not agrivoltaic, but they supply direct monofacial–bifacial cost comparisons that are rare in the agrivoltaic literature.

In agrivoltaics, albedo is partly a design variable that can be influenced by the choice of ground cover, so similar effects may be expected, although they have rarely been measured. A study of ground-surface effects under tropical conditions used a base discount rate of 9.4% for net present value (NPV) and LCOE, with a sensitivity range of 8.5-11% [81]. A UK study of tracking bifacial agrivoltaics found the lowest LCOE in the regions with the highest irradiance [82]. Table 6 lists the LCOE assumptions and sensitivity ranges used here.

The base-case parameters were taken from published ranges. The 5% discount rate represents concessional financing typical of development finance institutions, and the 8% high case approximates commercial lending. The specific-yield range of 1,400-2,100 kWh/kWp per year was chosen to match the irradiation envelope for Nigeria, where annual global horizontal irradiation is reported as 1,800-2,200 kWh m^{-2} a^{-1} in the north and about 1,800 kWh m^{-2} a^{-1} in the south [41]. The bifacial gain range of 8-20% is consistent with field and modelling results: a coupled optical-thermal-electrical model gave an annual bifacial gain of about 11.8% at albedo below 0.2, more than 17% at albedo above 0.4, and up to 32.7% at very high albedo [83]. A 25-year lifetime and 0.7% annual degradation are standard assumptions.

Table 6. LCOE assumptions and sensitivity ranges.

Parameter	Base case	Low	High
CAPEX (USD/Wp)	1.10	0.85	1.45
Discount rate (%)	5	3	8
Lifetime (years)	25	20	30
Annual degradation (%)	0.7	0.5	1.0
Specific yield (kWh/kWp per year)	1,750	1,400	2,100
Bifacial gain (%)	14	8	20
OPEX (USD/Wp per year)	0.015	0.010	0.020
LCOE (USD/kWh)	0.065	0.048	0.095

Sensitivity analysis indicates that bifacial systems reach a lower LCOE than monofacial equivalents when the bifacial gain exceeds about 8%. A field study in a desert climate found that a module with a bifacial gain of 8.6% was profitable provided the bifacial premium

did not exceed 10% of the monofacial module cost [84]. Below about 6% gain, monofacial systems may be preferable. The crossover point depends on the CAPEX premium, discount rate, and irradiance, and these thresholds should be read as indicative.

8.1.1 Nigerian context

Nigeria-specific techno-economic data for bifacial agrivoltaics are not yet available, so global design studies serve as the nearest benchmarks. A worldwide cost-based optimisation found that, compared with a monofacial farm, an optimised bifacial farm needs modules tilted about 15-20° higher and reduces LCOE by about 8-10% in many locations [85]. A global study of vertical bifacial farms found that, regardless of location, they yield 10-20% more energy than a traditional monofacial farm at a practical row spacing of 2 m [86].

A case study of agrivoltaics in Anambra State, Nigeria, found that solar agricultural systems achieved an LCOE of NGN 80/kWh, far below the NGN 736/kWh of diesel generators [87]. An economic-feasibility assessment of solar irrigation in sub-Saharan Africa indicates that stand-alone PV irrigation could meet a substantial share of crop water needs on small-scale farms [88].

8.2 Sustainability implications

The sustainability implications of the technology choice go beyond cost. Agrivoltaic systems, including bifacial configurations, have been associated with several benefits:

(i) *Lower land requirement.* Higher energy yield per unit area may allow bifacial systems to deliver the same output on less land, reducing competition for land and pressure on natural habitats, depending on system configuration [39, 89].

(ii) *Water efficiency.* Microclimatic changes under agrivoltaic arrays, especially higher soil moisture, have been linked to water savings in water-scarce regions [68, 69].

(iii) *Climate resilience.* Temperature moderation and drought protection under agrivoltaic arrays may reduce crop vulnerability to extreme weather [70, 90].

(iv) *Materials and manufacturing.* Glass-glass construction increases durability and service life but uses more material and makes modules heavier to transport. The 30-year warranty, compared with 25 years for monofacial modules, suggests longer service life and less frequent replacement [23, 24].

9 Case studies

9.1 Next2Sun vertical bifacial systems (Germany)

Next2Sun installations in Germany mount bifacial modules vertically in east-west rows, leaving sunlit strips between rows that can be farmed with standard machinery. Vertical orientation produces morning and late-afternoon generation peaks, when low sun angles favour rear-side capture. Optimisation studies of comparable vertical layouts show that row spacing can be tuned to balance electricity output and cultivable area [39, 52]. Published monofacial reference data from the same sites are not available, so these results do not isolate the effect of bifaciality.

A field assessment in Lahore, Pakistan, applied vertical bifacial agrivoltaics to vegetable production. The 10.5 kW system produced crop-specific responses, including a higher potato yield but lower okra and calabash biomass, together with higher soil moisture and slightly lower air temperature than the control [91].

9.2 Fraunhofer ISE APV-RESOLA (Heggelbach, Germany)

The APV-RESOLA research plot at Heggelbach, Germany, uses bifacial glass-glass modules mounted with a clearance of about 5 m above an arable rotation that includes potatoes and clover grass, and crop yields under the array have been reported for several seasons [13, 43]. Because the plot has no monofacial reference at the same height, it does not provide a matched comparison of module types.

9.3 Jack's Solar Garden (Colorado, USA)

Jack's Solar Garden in Colorado uses single-axis-tracking monofacial modules and has provided baseline data on crop responses under moving shade. Crops such as chiltepin peppers and tomatoes showed that tracker shade produces a heterogeneous light distribution and greater within-plot yield variability than in open-field controls [92]. Bifacial modules have not been measured at this site, so any projected benefit remains a modelling result.

9.4 Nigerian case studies

Interest in agrivoltaics is growing across developing countries, where adoption is limited mainly by finance,

Table 7. Decision-support matrix for choosing monofacial or bifacial PV in agrivoltaic systems.

Criterion	Threshold	Recommendation	Rationale
Albedo	> 0.35	Bifacial	High rear-side irradiance; reported LCOE reduction 4-19.6%, depending on site and financing
	0.25-0.35	Either	Marginal bifacial benefit; economic analysis required
	< 0.25	Monofacial	Bifacial gain $< 8\%$; unlikely to offset the cost premium
Crop type	Shade-tolerant (e.g., leafy C3 vegetables)	Bifacial	More uniform light; 40-60% shade acceptable
	Light-demanding (C4 crops, high-light C3 crops)	Monofacial, or bifacial with wide spacing	Avoid $> 20\%$ shade; wide alleys essential
Mounting height	> 2.5 m	Bifacial	Larger rear view factor; machinery access
	1.5-2.5 m	Either	Moderate bifacial gain (8-12%)
	< 1.5 m	Monofacial	Severe rear-side shading; bifacial gain $< 5\%$
Climate	High direct fraction ($> 70\%$)	Bifacial (with high albedo)	Largest absolute additional yield on reflective ground
	High diffuse fraction ($> 50\%$)	Either	Relative bifacial gain higher, but absolute yield lower
Land cost	High (>USD 10,000/ha)	Bifacial	Higher energy density per hectare
	Low (<USD 5,000/ha)	Monofacial	Land area less constrained
Capital constraint	Tight budget	Monofacial	Lower up-front cost (bifacial module premium about 3-7%, plus BOS costs in elevated designs)
	Flexible budget	Bifacial	Lower LCOE over 25-30 years
Row spacing	$> 2\times$ module height	Bifacial	Little rear shading; high bifacial gain
	$< 1.5\times$ module height	Monofacial	Severe rear shading; minimal bifacial gain
Maintenance	High-soiling environment	Monofacial	Rear-side cleaning difficult
	Low-soiling environment	Bifacial	Rear-side soiling manageable

Thresholds are indicative values from the reviewed literature, not fixed cut-offs. Local measurement and modelling are required before final technology selection.

policy, and technical capacity [93]. Geospatial analysis indicates that Nigeria's northern states combine water-stressed cropland, strong irradiance, and low electricity access, which makes them the most suitable regions for agrivoltaics [94].

9.4.1 *NASENI solar-powered irrigation prototypes*

In Jigawa and Kano States, the National Agency for Science and Engineering Infrastructure (NASENI) has deployed elevated solar structures (2.5-3 m) that power drip irrigation for tomatoes and onions, mainly to replace diesel pumps and improve irrigation reliability. The partial shade under the elevated modules reportedly lowers soil surface temperature by 4-6 °C and reduces evaporative demand. The region's high insolation and sandy loam soils (albedo 0.35-0.40) may favour bifacial retrofitting, because bifacial gain rises with ground albedo [11] and bifacial performance has been evaluated under Nigerian climatic conditions [41]; however, no site-level modelling or measurement has been reported for these sites. The installed systems are monofacial, and no direct monofacial-bifacial comparison exists at these sites.

9.4.2 *Private-sector agri-tech pilots*

In Nigeria's Middle Belt and southern regions, agri-tech start-ups have reportedly installed solar canopies over high-value horticultural crops to reduce sunscald and canopy temperature during critical growth stages, and these systems also power drip irrigation. The challenges and opportunities of such deployments in sub-Saharan Africa are reviewed in [95]. Field experiments with elevated agrivoltaic arrays in East Africa have reported combined crop, water, and electricity benefits, which suggests comparable potential in Nigeria [96]. Performance figures for the commercial pilots are reported by the vendors and have not been independently verified.

10 Challenges and future directions

10.1 Technical challenges

(i) *Uncertainty in yield prediction.* Bifacial yield predictions carry an uncertainty of about ±5-8%, compared with ±3-5% for monofacial systems, because rear-side irradiance is harder to model. Accurate prediction must account for albedo that changes with canopy development and soil moisture, and for uneven soiling on both module faces [97].

(ii) *Long-term reliability data.* Field data on glass-glass bifacial laminates under combined mechanical and electrochemical stress are limited, and few installations have more than 10-12 years of service [23, 24]. Modules are exposed simultaneously to wind-induced vibration, daily thermal cycling, and high-voltage bias that accelerates PID, particularly in humid tropical climates [55].

(iii) *Optimisation trade-offs.* Bifacial gain rises with ground albedo [15], but the agronomic side effects of engineered high-albedo surfaces (root-zone temperature, soil moisture, pest habitat) have not been quantified and need field study.

(iv) *Confounding of module type with system design.* As shown in Section 5.3, most field studies confound bifaciality with elevated mounting and wider spacing, which limits attribution of benefits to module type. Future studies should use matched configurations.

10.2 Future technological prospects

(i) *Optical modelling.* High-resolution optical models that represent irregular terrain and canopy geometry are being developed and validated against field data [98, 99]. They will allow more accurate simulation of changing albedo and better system design.

(ii) *Cell architecture.* The shift from PERC to tunnel-oxide passivated contact (TOPCon) and silicon heterojunction (HJT) cells is expected to raise bifaciality factors from the current 70-81% to above 90% [100]. Rear-side efficiency would then approach front-side efficiency, although the rear surface still receives far less irradiance than the front.

(iii) *Spectral management.* Modules with dichroic filters or luminescent solar concentrators that transmit PAR wavelengths and convert the remaining spectrum to electricity could reduce the competition between energy and crop production. Luminescent concentrators have so far been demonstrated mainly for greenhouses [101], and concentrating agrivoltaic concepts are reviewed in [102].

(iv) *Dynamic control.* Studies of midday photosynthetic depression under agrivoltaic shade and of intermittent versus constant shading in rice provide the physiological basis for dynamic shade control [103, 104]. Tracking algorithms that adjust shading to crop development stage and daily stress patterns could turn agrivoltaic arrays into active crop-management tools, but they remain to be developed and validated in the field.

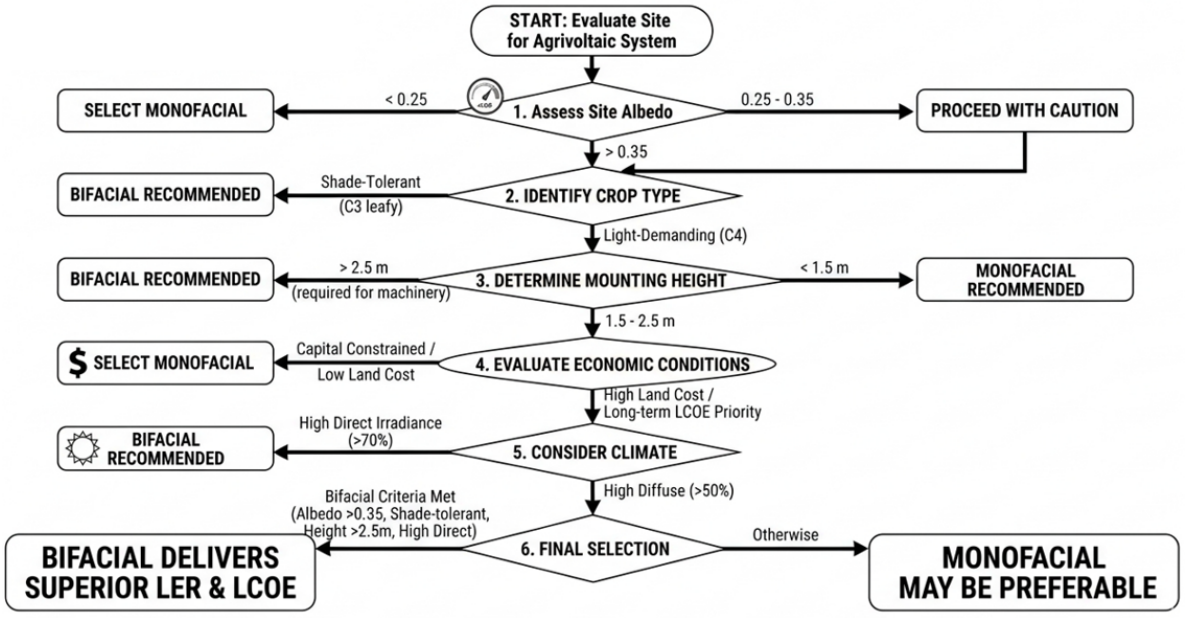

Figure 9. Decision flowchart for selecting monofacial or bifacial PV modules in agrivoltaic systems from site and economic criteria.

11 Conclusions and recommendations

11.1 Conclusions

Monofacial and bifacial modules suit different agrivoltaic settings. Monofacial modules have lower capital cost and fit low-albedo or budget-constrained sites, but their opaque backsheets produce strongly heterogeneous light and soil-moisture patterns that require careful crop selection. Bifacial glass-glass modules, usually installed with more than 2 m clearance, give more uniform light under the array and higher energy per unit of land, but much of the reported advantage comes from the elevated, widely spaced geometry rather than from bifaciality itself. Reported LER ranges for the two technologies overlap, and the highest values come from tracking or vertical designs. Bifacial systems are favoured where albedo exceeds about 0.35, clearance exceeds 2 m, and row spacing is generous; the module premium, higher structural cost, and $\pm$5-8% prediction uncertainty mean that each project needs integrated planning.

The evidence base has three main weaknesses: few direct comparisons under identical agrivoltaic conditions, frequent confounding of module type with mounting geometry, and scarce long-term data from tropical sites. Claims that bifaciality itself improves crop yield, spectral quality, or plant morphology need to be tested in matched-configuration field trials with direct spectral measurements.

11.2 Decision-support framework

The review findings are summarised as selection criteria in Table 7.

Table 7 groups the evidence into eight criteria (albedo, crop type, mounting height, climate, land cost, capital constraint, row spacing, and maintenance), each with thresholds, a recommendation, and a rationale. Figure 9 arranges the main criteria as a decision flowchart that starts with site albedo and proceeds through crop type, mounting height, economic conditions, and climate.

11.3 Recommendations

(i) *Site-specific assessment.* Evaluate local albedo, crop light requirements, mounting height, machinery access, and economics with coupled optical and crop-growth models before fixing the array geometry, using Table 7 as a starting point.

(ii) *Demonstration networks.* Establish comparative demonstration sites across agro-ecological zones with monitoring of energy, microclimate, crop yield, and economics. Give priority to matched-configuration trials that separate module-type effects from system-design effects, and to crop-specific shade-response studies for staples, horticultural crops, and climate-adapted varieties.

(iii) *Policy and incentives.* Integrate agrivoltaics into agricultural extension, renewable energy incentives, and land-use planning, and make dual-use systems eligible for both agricultural and energy support. Techno-economic analysis of agrophotovoltaics shows that policy support affects the price-performance ratio, so technology-neutral, performance-based incentives should reward combined energy and crop outcomes [105].

(iv) *Capacity building.* Train engineers, agronomists, and extension workers in technology selection and system design, and share results through farmer demonstrations, extension programmes, and digital platforms.

(v) *Long-term reliability.* Monitor performance, degradation, and operating costs over the long term to reduce financial uncertainty, and develop agriculture-specific modules with adapted cell spacing, anti-soiling coatings, and spectral management.

(vi) *Local economic assessment.* For Nigeria and other Sub-Saharan African countries, base economic assessments on local module prices, interest rates, land costs, import tariffs, and electricity tariffs.

Data Availability Statement

No new data were generated in this study. The data-extraction form and study-level data are available from the corresponding author upon reasonable request.

Funding

This work was supported without any funding.

Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable. This article is a literature review and did not involve human participants or animals.

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