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Horticulture-Voltaic: The Earth's Solar Horticulture Turns Every Ray into Food and Power - A Comprehensive Review

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Abstract— *Horticulture-voltaic systems - the co-location of photovoltaic (PV) electricity generation with horticultural crop production on the same land - are emerging as a central strategy for climate-resilient horticulture. This in-depth review examines the technology, engineering, intercultural operations and empirical evidence for horticulture-voltaics applied to fruit, vegetable and flower crops. We cover solar panel technologies, system architectures, the full design-component and engineering stack (mounting heights of 2.5-5 m, panel spacing and tilt, deep-buried armoured cables, structural safety under ASCE-7-16 wind loads, smart irrigation integration), the electrical architecture (module/string voltage, inverter, battery, transformer, grid connection), and intercultural operations adapted for sub-array horticulture. Empirical evidence shows that shade relieves heat and drought stress, with grape +277% (Mediterranean, LER 3.54), tomato and chiltepin doubled or tripled (Arizona), and partial shade increasing floral abundance in flowers. Shading must stay below ~30% for fruit crops and 20-40% for most vegetables and flower crops. With continued research and engineering, horticulture-voltaics can deliver climate-adaptive, resource-efficient and energy-positive horticultural systems.*

Keywords— agrivoltaics; horticulture-voltaic; climate-resilient horticulture; photovoltaic; solar energy; fruit crops; vegetable crops; flower crops; shading; ground coverage ratio; wind load; intercultural operations.

I. INTRODUCTION

Horticulture-voltaic systems - the co-location of photovoltaic (PV) electricity generation with horticultural crop production on the same land - are emerging as a central strategy for climate-resilient horticulture. The concept of agrivoltaics (agri-PV, or AV) was first proposed by Goetzberger and Zastrow (1982) and has since grown from a niche idea into a rapidly expanding global field of research and commercial deployment [1,2]. The core proposition is dual land use: solar panels generate electricity while the shade they cast moderates the microclimate beneath, reducing heat and drought stress, lowering evaporative demand and, in hot dry regions, often improving crop performance and water-use efficiency [3,4].

The rationale is compelling. Global food demand is projected to rise by 35-56% by 2050 while agricultural land is finite, and the transition to renewable energy requires large land areas; co-locating the two uses avoids the land-use conflict between food and energy [4,5]. Empirical studies report that agri-voltaic arrays can raise land-use efficiency above 180% - producing electricity and crops on the same hectare - while cooling panels (improving their electrical efficiency) and cooling the crops and soil beneath [4,6].

For horticulture the stakes are especially high. Perennial fruit crops (apple, grape, citrus, fig, olive, pomegranate), high-value vegetables (tomato, chilli, brinjal, leafy greens) and flower crops (rose, gerbera, marigold, chrysanthemum, tuberose) are increasingly exposed to heat waves, drought, salinity and erratic weather. The shade, cooler soil and conserved soil moisture under PV arrays offer a measurable resilience benefit [7,8]. At the same time the same shade can reduce yield and quality if it exceeds crop-specific thresholds: for fruit crops, shading above roughly 30% risks substantial declines [9,10].

This review provides an in-depth, engineering-oriented account of horticulture-voltaic systems, restricted to horticultural crops - fruits, vegetables and flower crops. It covers the solar technology models, system architectures, mounting designs, electrical architecture, infrastructure and installation components, engineering design parameters, intercultural operations adapted for sub-array cropping, and empirical evidence and ongoing research supporting the technology, with four labelled diagrams for systems engineering, design components, intercultural operations, and electrical schematics.

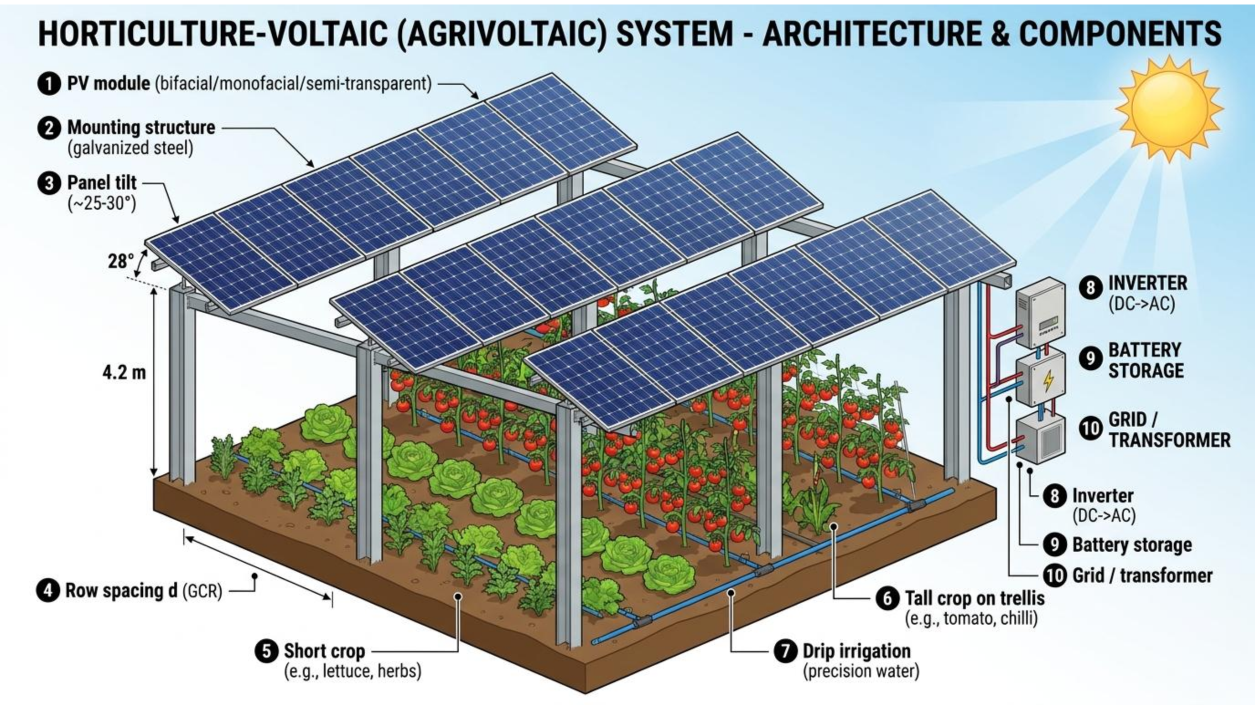

FIGURE 1: Three-dimensional architecture of a horticultural-voltaic system showing elevated PV modules on mounting structures, crops beneath, drip irrigation, and electrical components (inverter, battery, transformer). Numbered labels 1-10 identify all design elements.

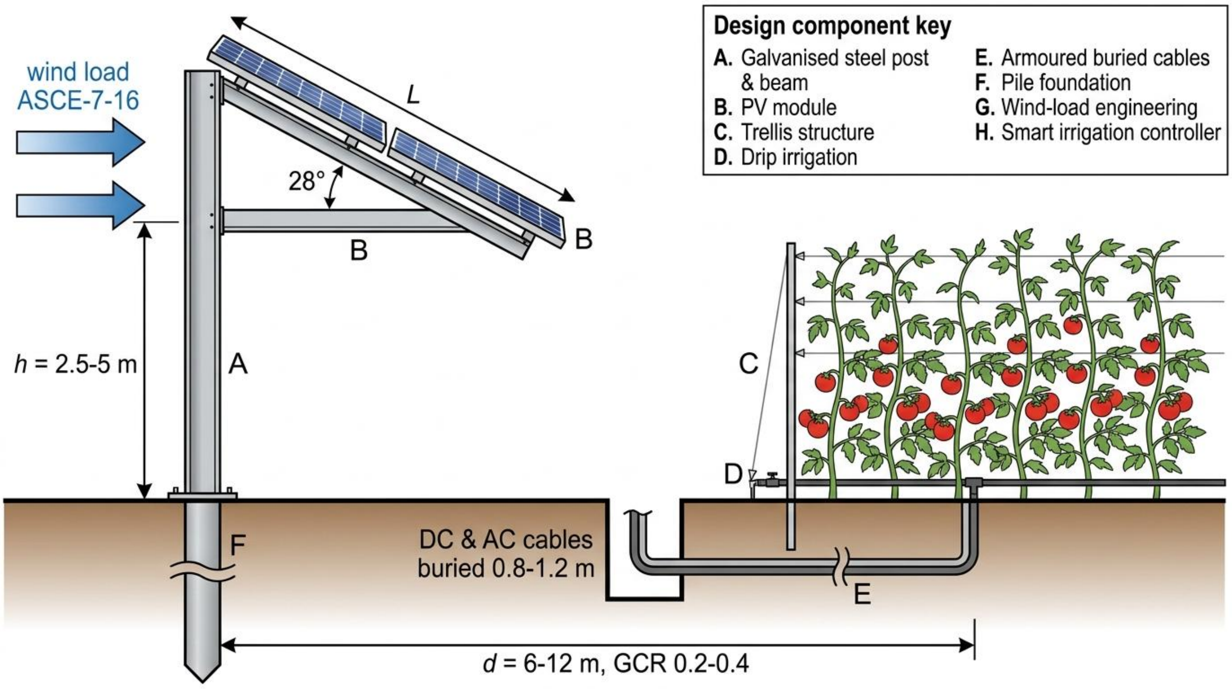

FIGURE 2: Engineering design components and dimensional layout: mounting height (h = 2.5-5 m), panel tilt (28 degrees), row spacing (d = 6-12 m, GCR 0.2-0.4), trellis structure, drip irrigation, armoured buried cables and wind-load annotations (ASCE-7-16); design component key A-H.

II. REVIEW METHODOLOGY

This narrative review was prepared by synthesizing peer-reviewed literature on horticulture-voltaic systems with a focus on fruit, vegetable, and flower crops. Literature was identified through targeted searches of major scientific databases including Web of Science, Scopus, ScienceDirect, Google Scholar, and PubMed Central using search terms such as "agrivoltaics," "horticulture-voltaic," "agri-PV," "photovoltaic," "shading," "fruit crops," "vegetable crops," "flower crops," and "climate-resilient horticulture." The search covered the period from 1982 (the foundational Goetzberger and Zastrow paper) to 2026, with emphasis on recent developments from 2019 onwards. Foundational papers necessary to define the field were also included. Studies were included if they addressed agrivoltaic systems, horticultural crop production under PV arrays, or related engineering and microclimate aspects. The retrieved literature was critically evaluated for scientific quality, relevance, and contribution to the understanding of horticulture-voltaic systems.

III. SOLAR PHOTOVOLTAIC TECHNOLOGY MODELS

The PV module is the fundamental building block; its technology determines efficiency, light transmission, cost and suitability for a given crop and architecture. Table 1 summarises the principal panel types relevant to horticulture-voltaic systems.

TABLE 1
PRINCIPAL PHOTOVOLTAIC PANEL TYPES AND THEIR ROLE IN HORTICULTURE-VOLTAIC SYSTEMS

Panel type	Typical efficiency	Light transmission	Agrivoltaic role	Source / Notes
Monofacial crystalline silicon (c-Si)	18-22%	Opaque	Standard elevated arrays	Mature, low cost; common baseline
Bifacial c-Si	18-23%	Opaque (rear captures albedo)	Elevated + vertical arrays	+5-30% energy vs monofacial [11]
Thin-film (CdTe, a-Si, CIGS)	12-18%	Semi-transparent options	Diffuse-light arrays; Laterza vineyard system [9]	Uniform shading; low temperature coeff.
Semi-transparent / spectral-splitting	8-15% (transmission-adjusted)	20-60%	Greenhouses, high-value crops	Tunable PAR vs NIR; crop-friendly light [12]
Organic / dye-sensitised (OPV/DSSC)	5-12%	Tunable, coloured	Emerging, niche	Flexible, low cost, early stage
Perovskite (emerging)	25%+ (lab)	Tunable	Research stage	High potential; stability/toxicity to resolve

Bifacial modules are particularly attractive for agri-voltaics because the rear face harvests light reflected from soil and crops, adding 5-30% energy output, and because they enable vertical and elevated geometries that leave more light for crops [11,13]. Semi-transparent and spectral-splitting modules are the key to greenhouse-integrated and high-value-crop systems: they can pass photosynthetically active radiation (PAR) while converting near-infrared into electricity, or simply trade a controlled fraction of light for power [12].

IV. SYSTEM ARCHITECTURES AND MOUNTING MODELS

Agri-voltaic systems are classified by their geometry and mounting. The main architectures relevant to horticulture are:

4.1 Elevated fixed-tilt (pergola / canopy) arrays:

Panels are mounted on elevated structures several metres above the ground, tilted typically 20-35 degrees. This is the most common architecture for field vegetables and berries. The clearance height (panel underside to soil) is the key crop-compatibility parameter: 2.5-4 m for field vegetables, 4-6 m for orchards and vineyards to allow machinery and tall crops [14,15]. Examples include the Fraunhofer APV-RESOLA system at Heggelbach (Germany) [6] and the Ferrara/Bari sites in Italy [9].

4.2 Single-axis and dual-axis tracking arrays:

Panels rotate to follow the sun. Trackers raise annual energy yield by 20-35% (single-axis) relative to fixed tilt, but moving structures cast dynamic shade that can be managed to protect crops during heat peaks or to maximise light in cool seasons [16]. The Scalea (Calabria) lemon trial directly compares fixed panels against single-axis trackers [17].

4.3 Vertical bifacial arrays:

Panels are mounted vertically, facing east-west, in rows between crop strips. This geometry minimises shading of the crop (shade is brief and passes), allows full mechanisation between rows, and suits horticultural rotations. Vertical bifacial systems are well documented in Belgium and Germany [11,18].

4.4 Semi-transparent and diffuse-light arrays:

Panels with reduced or tuned transmission spread light more evenly, reducing hot spots and allowing crops to be grown directly beneath. These are favoured for high-value, shade-tolerant crops and for greenhouse integration [12].

4.5 Greenhouse-integrated (rooftop) PV:

Panels are mounted on or integrated into greenhouse roofs, generating power while the greenhouse continues to produce vegetables and flowers. Semi-transparent modules on the roof balance light for the crop with electricity output - the "electricity above, crop below" model [19].

4.6 Floating agri-voltaics (emerging):

Panels float on water bodies; relevant where land is scarce.

V. ENGINEERING DESIGN COMPONENTS

Engineering design is what makes horticultural integration possible while keeping the array safe and durable. The principal design components (Figure 2) are:

5.1 Elevated and vertical structures:

Panels are typically mounted 2.5 to 5 m (6-12 feet) high to allow standard farm machinery and tractors to pass underneath, or configured as vertical bifacial arrays to accommodate large commodity equipment like combines [14,20]. Mounting structures are typically hot-dip galvanised steel or aluminium; posts are sized for wind, snow and crop loads with the larger heights raising the wind-load design values per ASCE-7-16 [21,22]. The first row of panels is generally taller and stronger than subsequent rows to carry asymmetric loading; field data show meaningful differences between upstream and sheltered downstream rows in vertical arrangements [22].

5.2 Panel spacing and tilt:

Rows and individual modules are spaced further apart than in traditional solar farms to control the shading ratio and ensure sufficient sunlight filters down for crop photosynthesis [14,15,20]. Tilt is typically 20-35 degrees (28 degrees is widely used); the structure can be designed for adjustable tilt to suit seasonal radiation. The ground coverage ratio (GCR = panel area / land area) directly controls the shading fraction; for fruit crops shading should stay below ~30% (GCR roughly 0.3-0.4) [10,15].

5.3 Electrical and wire management:

Underground DC and AC cables must be installed at a greater depth than typical PV installations - armored and buried 0.8-1.2 m deep - to prevent damage during tilling, plowing and heavy agricultural groundwork [20,23]. Cable routes must avoid cultivation zones or be armoured; combiner boxes and isolators should be at serviceable heights. Partial shading from crops/structures is mitigated with module-level optimisers or micro-inverters [23].

5.4 Structural safety and wind loads:

Engineering frameworks must account for increased wind loads on taller columns; builders design customisable adjustments based on local disaster resistance (cyclone, tornado, hail) and terrain [14,20,22]. Considerations include ASCE-7-16 wind-pressure coefficients, exposure category and panel height; a 3D CFD study showed meaningful pressure differences between panels in different positions of a vertical array [21,22]. Bolted base plates, pile-driven foundations, or concrete piers are used depending on soil and water table.

5.5 Smart irrigation integration:

Irrigation lines (overhead or buried drip) are mapped into the initial PV layout to optimise water delivery and avoid operational conflicts with the structure and cabling [20,24]. Smart controllers integrate soil-moisture sensors, weather data and module-level ET models to schedule variable-rate irrigation; the agri-voltaic array's shade reduces crop water demand by up to 70% in arid or high-heat environments, so the irrigation controller can save the corresponding energy and water.

5.6 Re-tillage reversibility:

Because land is farmland, foundations should minimise soil disturbance and be reversible at the end of the array's life. Pile-driven or screw foundations are preferred over concrete slabs for this reason [20].

VI. ELECTRICAL SYSTEM ARCHITECTURE

A horticultural-voltaic system is a complete PV power plant plus storage and monitoring. The electrical architecture (Figure 4) is summarised in Table 2.

TABLE 2
ELECTRICAL SYSTEM ARCHITECTURE OF A HORTICULTURAL-VOLTAIC ARRAY

Stage	Component	Typical specifications	Notes
Module	PV module	400-600 Wp, Voc 40-50 V	c-Si or bifacial
String	Series-parallel of modules	20-35 modules, 600-1500 Vdc	String voltage stays within inverter MPP window
DC side	DC cabling + combiner box + SPD	4-6 mm² PV cable, 0.8-1.2 m burial	Armoured for tillage
Conversion	String inverter	1000/1500 Vdc to 230/400 Vac	Micro-inverters for partial-shade cases
Storage	Battery rack	5-50 kWh (Li-ion / LFP)	Self-consumption + farm loads
Distribution	AC distribution + transformer	11-33 kV MV for export	230/400 V three-phase for on-farm loads
Grid	Meter + protection	Net metering / feed-in tariff	Compliance with DISCOM regulations

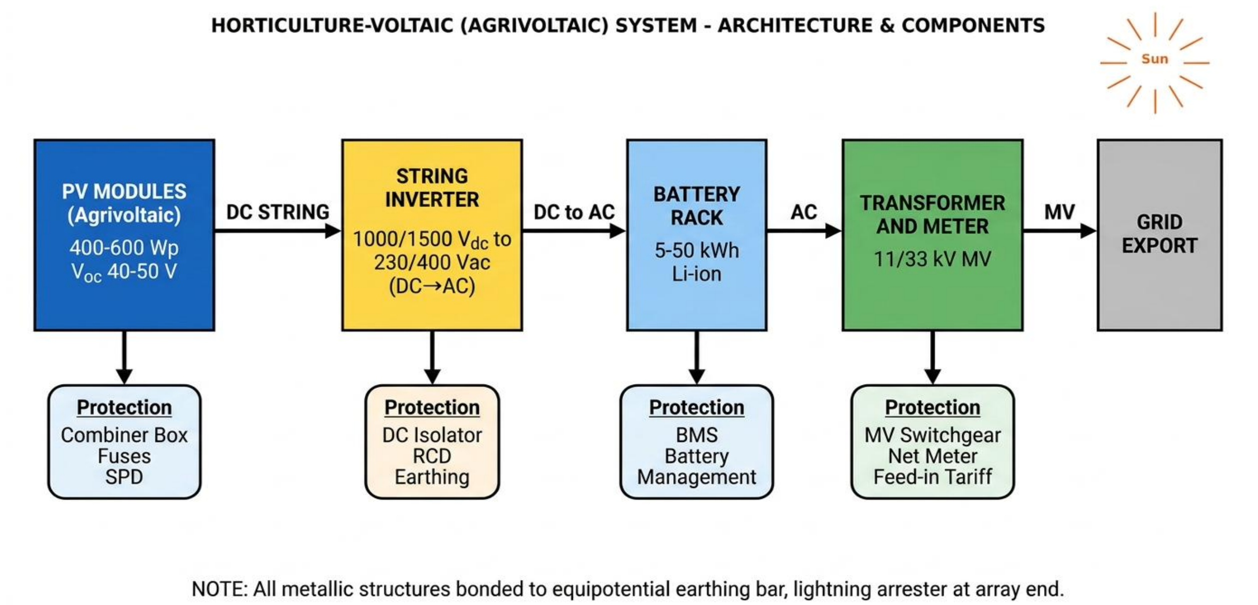

FIGURE 3: Electrical schematic of an AV system from PV modules (Voc 40-50 V, 400-600 Wp) through string inverter, battery rack, transformer and grid connection, with protection and monitoring stages.

A single c-Si module typically delivers an open-circuit voltage (Voc) of ~40-50 V and a maximum-power voltage (Vmp) of ~30-40 V at a power of 400-600 Wp. Modern inverters accept a maximum system voltage of 1000 Vdc or 1500 Vdc, which sets the maximum string length (typically 20-35 modules) [23]. The string must stay within the inverter's MPP (maximum power point) voltage window and below the maximum voltage at cold temperatures (when Voc rises) [23,25].

VII. INFRASTRUCTURE AND INSTALLATION

The physical infrastructure comprises mounting structures (galvanised steel or aluminium), foundations (pile-driven posts, ground screws or concrete ballast), cabling and cable management (armoured, deep-buried), water infrastructure (drip lines, sensors, optional water treatment such as reverse osmosis) and balance-of-system (BOS) cabinets housing inverters, batteries, transformers, metering, monitoring and protection [14,20,23].

Access and machinery clearance are critical: row spacing must accommodate tractors, sprayers and harvest machinery; orchard structures span between tree rows so equipment can pass beneath [14,20]. For elevated systems, increasing the structural height raises material costs and wind-load design values, so mounting structure is sized to the minimum clearance required for the chosen crop and machinery [21,22,26].

VIII. INTERCULTURAL OPERATIONS UNDER AN AGRI-VOLTAIC ARRAY

Intercultural operations are the routine field practices carried out after planting/sowing but before harvesting - weeding, hoeing, mulching, training, pruning, thinning, staking, plant protection and so on. Under an agri-voltaic array these operations must be adapted to the geometry, shaded microclimate, machinery clearance and cabling layout. The main classes (Figure 3) are:

8.1 Soil and weed management:

Under partial shade the soil is cooler and wetter than in full sun, which slows weed germination but also favours certain moisture-loving weeds. Regular weeding (manual, mechanical or chemical) is therefore still required; shallow hoeing breaks the soil crust and aerates around the root zone without damaging shallow-buried drip lines and armoured cables [27,28]. Mulching - with organic materials (straw, leaves) or plastic sheets - further suppresses weeds, conserves soil moisture and regulates soil temperature; it is one of the most effective intercultural operations in shaded systems. Earthing-up - piling soil around the stem base - is essential for tuber crops (potato, ginger) and cabbages, and is generally compatible with array structure provided post spacing allows [27].

8.2 Canopy and growth regulation:

Training the plant on a trellis (grape, tomato, kiwi, passion fruit, certain flower crops) directs growth, optimises light interception and reduces the risk of branches breaking under their own weight. Pruning systematically removes dead, diseased or overcrowded branches to balance vegetative growth with reproduction and improve air circulation; in fruit trees and grapevines, pruning interacts directly with the shading pattern imposed by the array and must be timed to keep the canopy alert to photosynthetically beneficial periods without excessive shading [27,29]. Thinning - removing excess flowers, buds or immature fruits - prevents branch breakage, increases the size and quality of remaining fruits, and is a standard practice in grape, apple, peach, mango and citrus [27,29]. Pinching (removing terminal growing tips to encourage lateral branching) is standard in flower crops like marigold and carnation; desuckering (removing non-productive vegetative shoots) is essential in banana and tomato [27].

8.3 Crop protection and support:

Staking (bamboo sticks, wooden stakes, strings) prevents tall or weak-stemmed crops (tomato, pea, carnation) from lodging under their own weight; the array's posts can serve as a structural backbone for vertical-string systems. Blanching (tying outer leaves over cauliflower heads) keeps them white; wrapping individual pomegranate fruits, fig fruits or grape bunches protects them from sun-scald, birds and hail - particularly valuable because the array's shade reduces but does not eliminate sun-scald risk [27,28]. Plant protection (targeted bio-pesticides, fungicides, insecticides) follows integrated pest management (IPM) principles; the agri-voltaic microclimate's altered humidity may shift pest pressure and disease cycles and requires adapted spray timing [27,28].

8.4 Operations adapted to the AV microclimate:

The agri-voltaic microclimate (lower air temperature at midday, higher night temperature, lower vapour-pressure deficit, less wind speed, more uniform light) calls for specific cultivation adjustments [9,29]: selecting shade-tolerant cultivars; adjusting row orientation along the array's east-west axis to maximise morning light; choosing machinery sized to the array's clearance; and modifying planting schedules so flowering and fruiting windows coincide with the array's most beneficial shading periods (e.g., shade during afternoon heat peaks in summer for leafy vegetables and flowers). Mulching and drip irrigation scheduling must coordinate with the array's drip line plan and with the increased soil-moisture retention that shading provides [24,27].

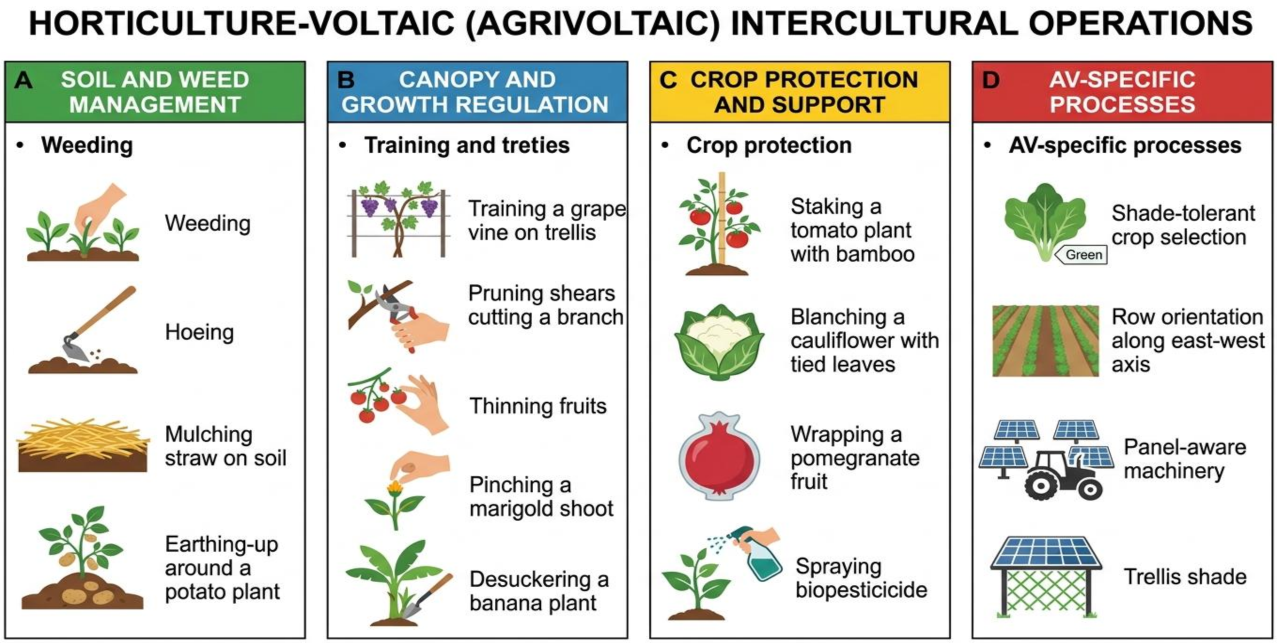

FIGURE 4: Intercultural operations for horticultural crops under an agrivoltaic array: soil and weed management, canopy and growth regulation, crop protection and support, and AV-specific processes.

IX. SUITABILITY OF HORTICULTURAL CROPS

Engineering design determines whether a crop thrives or suffers under the array. The principal parameters are GCR, panel height vs crop height plus machinery envelope, tilt, row spacing and PAR transmission [10,14,15]. Table 3 summarises the suitability of horticultural crops for agri-voltaic installation.

TABLE 3
SUITABILITY OF HORTICULTURAL CROPS (FRUITS, VEGETABLES, FLOWER CROPS) FOR AGRI-VOLTAIC INSTALLATION

Crop group	Examples	Height class	Shade tolerance	Recommended shading
Leafy vegetables & herbs	Lettuce, spinach, chard, kale, basil, mint	Low (<0.5 m)	High	30-50%
Fruiting vegetables	Tomato, chilli, brinjal, sweet pepper	Tall (trellised)	Medium	20-35% (heat-stress relief)
Root & other vegetables	Onion, garlic, carrot, radish	Low-medium	Medium	20-30%
Berry fruits	Strawberry, raspberry, blueberry	Low-medium	Medium-high	20-40%
Vine fruits	Grape (table/wine)	Tall (trellis)	Medium	<30% (quality-sensitive)
Pome & stone fruits	Apple, peach, plum	Tree (2-4 m)	Medium	<30%
Citrus & subtropical fruits	Lemon, orange, fig, olive, pomegranate	Tree	Medium-high	<30-40%
Flower crops (cut & loose)	Rose, gerbera, marigold, chrysanthemum, tuberose	Low-medium	Medium-high	20-40% (partial shade often improves floral abundance) [30]

X. EMPIRICAL EVIDENCE: FRUIT CROPS

Fruit crops are the most extensively studied horticultural group under agri-voltaics. Shade relieves heat and drought stress but can reduce yield and quality beyond a threshold.

10.1 Grapevine:

Magarelli, Mazzeo and Ferrara (2025) at Laterza (Puglia, Italy) report that Primitivo grapevines beneath a fixed thin-film (a-Si) array covering 43% of the ground yielded +277% more grapes than vines in full sun, with better bud fruitfulness; the array reduced wind speed and vapour-pressure deficit and the land equivalent ratio (LER) reached 3.54, demonstrating high dual-use efficiency in Mediterranean conditions [9]. Earlier work by Juillion et al. (2022) in southern France showed tracking photovoltaic panels reduced temperature by ~3.8 degrees C and increased humidity by 14% in an apple orchard at 50-55% shading, reducing irrigation requirements by 6-31% and alternate bearing, but also reduced photosynthetic capacity with negative effects on flowering and yield [29].

10.2 Apple:

Juillion et al. (2022) reported fruit dry-matter content under shading was reduced by an average of 24%, and concluded that agrivoltaic systems may reduce alternate bearing while requiring careful management of shading below ~40% to preserve yield [29,31]. The Bari group's 2024 review with Ferrara recommended holding shading below a 30% threshold to avoid substantial declines in fruit yield and quality [10].

10.3 Citrus and subtropical fruits:

At Scalea (Calabria), ENEA and EF Solare Italia built a lemon trial running lemons under fixed panels against lemons under single-axis trackers, with bifacial modules, a lithium battery rack (5.12-20.48 kWh) and a reverse-osmosis unit converting brackish water to up to 240 L/h [17]. Ferrara's group is tracking lemon and lavender there; the two Italian sites (Laterza and Scalea) are designed to complement each other by testing different crops, environments and PV configurations [17].

10.4 Fig and olive:

At the Vigna Agrivoltaica di Comunita at Laterza (Taranto), a 970 kW array of ~7,770 thin-film panels (135 W, 125 W and 100 W) tilted at 28 degrees on reinforced concrete pergola frames is being used to study fig and olive under the glass [17]. Ferrara reported soil under the array more than 20 degrees Celsius cooler than soil in open sun at ~11 a.m. on a hot day, though he flagged this as a peak and noted it moves with latitude, time of day, ambient temperature and soil characteristics [17].

XI. EMPIRICAL EVIDENCE: VEGETABLE CROPS

Vegetables show the clearest yield benefits under agri-voltaics in hot, dry conditions, because heat and water stress relief outweigh light reduction.

11.1 Tomato:

Barron-Gafford et al. (2019) at Biosphere 2 (Arizona) found cherry tomato production was twice as great under PV panels than in the open field, with chiltepin pepper fruit production three times greater; jalapeno produced similar fruit with 65% less transpirational water loss, and soil moisture remained ~15% higher in the agri-voltaic system [4]. A Fraunhofer ISE pilot for Maharashtra (India) projected up to 40% higher yields for tomato under agri-voltaic shading [6]. A Princeton modelling study (Hosseini and Bou-Zeid, 2024) coupled air-heat-moisture simulation over a New Jersey tomato field; simulated leaves were 1.84-7.56 degrees C cooler under panels, with 47% less direct sunlight, 31% lower photosynthesis, 22.4% lower daily leaf water loss (42.6% for crops and soil) and 4.46 degrees C lower perceived temperature for farm labour; panels themselves ran 5.6 degrees C cooler, trimming heat-related efficiency losses by 15% [32].

11.2 Chilli and pepper:

The Arizona results for chiltepin (3x fruit) and jalapeno (similar yield, -65% transpirational water loss) are the strongest pepper evidence [4]. Many chilli/pepper types tolerate a 35-50% reduction in PAR compared to open sunlight, making them well suited to agri-voltaic installation [33].

11.3 Brinjal (eggplant):

Brinjal is heat- and drought-sensitive; agri-voltaic shade relieves heat stress and conserves soil moisture, though shading should be kept moderate (20-35%) to avoid yield loss [7,33].

11.4 Leafy vegetables and herbs:

Leafy greens (lettuce, spinach, chard, kale) and herbs (basil, mint) are shade-tolerant and among the most suitable crops for agri-voltaics, with stable or improved yields at 30-50% shading under hot and water-limited conditions [7,33].

XII. EMPIRICAL EVIDENCE: FLOWER CROPS

Flower crops (ornamentals and cut flowers) are an emerging but promising horticultural category for agri-voltaics, because many flower species are adapted to partial shade and benefit from reduced heat stress and moderated microclimate.

12.1 Partial shade and floral abundance:

Oregon State University research found floral abundance was greatest in partial-shade plots, with 4% more blooms than full-sun or full-shade plots, with benefits most pronounced in late summer when heat stress is highest [30].

12.2 Rose and gerbera:

Rose and gerbera are high-value cut flowers grown in greenhouses and shade houses; semi-transparent and greenhouse-integrated PV can supply electricity while preserving light quality for flower development [12,19]. Gerbera is routinely produced under shade nets in tropical regions, making it well suited to diffuse-light agri-voltaic systems.

12.3 Marigold, chrysanthemum and tuberose:

Marigold and chrysanthemum are photoperiodic loose-flower crops that respond to light quality and day length; partial shading can be managed to modulate flowering while protecting blooms from heat damage. Tuberose, a shade-tolerant bulbous flower, performs well under partial shade [27]. These crops are candidates for agri-voltaic installation in tropical and subtropical floriculture belts.

12.4 Design considerations for flower crops:

Because flower value depends on visual quality (colour, stem length, vase life), light management must be precise: semi-transparent panels that transmit PAR while converting NIR are preferable, and shading should be kept in the 20-40% range [12,30].

XIII. ONGOING RESEARCH AND EMERGING SYSTEMS

13.1 Multi-site field networks:

The University of Bari, ENEA, Agridatalog and partner companies run complementary trials at Laterza (fig, olive, grape under fixed pergola arrays) and Scalea (lemon, lavender under fixed vs tracking bifacial arrays), generating paired microclimate and yield data across different crops and PV configurations [9,17].

13.2 Modelling and digital twins:

Coupled physics models (air-heat-moisture) such as the Princeton tomato model [32], irradiance models for orchard integration and digital-twin approaches are being used to simulate shading, microclimate and crop response before field deployment.

13.3 Crop-specific shading thresholds:

Research is converging on crop-specific shading ceilings: ~30% for fruit crops [10], 20-40% for most vegetables and flower crops [7,30] - and on dynamic tracking strategies that protect crops during heat peaks while maximising light in cool seasons [16,29].

13.4 Greenhouse and protected-cultivation integration:

Semi-transparent rooftop PV for greenhouses producing vegetables and flowers is an active area, balancing electricity output with PAR transmission [12,19].

13.5 Wind-load engineering:

Field studies and CFD simulations of wind loads on elevated and vertical arrays are informing revised design codes for taller agri-voltaic columns [21,22].

13.6 Water-energy-food integration:

Systems pairing PV with drip irrigation, battery storage and water treatment (e.g., reverse osmosis at Scalea) are demonstrating the water-energy-food nexus in practice [17,24].

XIV. CHALLENGES AND FUTURE DIRECTIONS

Despite rapid progress, several challenges limit adoption:

14.1 Shading and yield trade-off:

Shade relieves heat stress but can reduce yield and quality beyond thresholds; for fruit crops shading must stay below ~30%, and for quality-sensitive crops (grape for wine, apple) the light environment must be managed carefully [9,10,29].

14.2 Capital cost and structure:

Elevated, orchard-spanning structures are costlier than ground-mounted arrays; foundations, galvanised steel and cable management must be engineered for 25+ year service [14,21]. The higher initial investment requires careful economic analysis, though the dual revenue streams (crop + electricity) can improve returns over time.

14.3 Crop-specificity and generalization:

Yield responses are crop- and site-specific; the same array can raise one crop and reduce another, so design must be tailored to crop height, shade tolerance and local climate [7,9].

14.4 Electrical and safety complexity:

String design, MPP voltage windows, inverter selection, battery sizing and safety clearances require specialist engineering; partial shading of modules by crops/structures must be managed with optimisers or micro-inverters [23].

14.5 Intercultural and operational complexity:

Agricultural operations - weeding, pruning, spraying, harvesting - must be adapted to the array's geometry and clearance; training, mulching and pinch management interact with the altered microclimate in counter-intuitive ways [27,28].

14.6 Skills and regulation:

Growers and extension staff need training in PV engineering, data systems and microclimate-aware cultivation; grid-connection, land-use and subsidy regulations vary by region.

14.7 Economic viability:

The economic viability of horticulture-voltaic systems depends on several factors: capital costs (which can be 2-3 times higher than ground-mounted PV due to elevated structures), crop revenue, electricity revenue, and operational costs. Payback periods typically range from 8-15 years depending on location, crop value, and electricity tariffs. Government subsidies and feed-in tariffs can significantly improve economic returns. For smallholder farmers, the high upfront costs remain a barrier, though leasing models and community-owned systems are emerging as alternatives.

14.8 Policy and regulatory considerations:

Regulatory frameworks for agrivoltaics vary widely across regions. Key considerations include: land-use classification (whether the land remains classified as agricultural), grid connection regulations, feed-in tariffs and net metering policies, building permits for elevated structures, and agricultural subsidies. Some countries (e.g., Germany, France, Japan) have established specific regulatory frameworks for agrivoltaics, while others are still developing them. Clear policy frameworks are essential for scaling up horticulture-voltaic deployment.

Future directions include: dynamic tracking programmed for crop protection; semi-transparent and spectral-splitting modules tuned to crop PAR needs; digital twins and AI for design optimisation; integrated water-energy-food systems; and standardised, open data ecosystems linking microclimate, yield, intercultural practice and energy data across sites [11,16,24,27,32].

XV. CONCLUSION

Horticulture-voltaic systems offer a compelling route to climate-resilient horticulture by producing renewable electricity and protecting fruit, vegetable and flower crops on the same land. The shade, cooler soil and conserved moisture under PV arrays relieve heat and drought stress: grape yield rose by 277% under a Mediterranean array, tomato and chiltepin production doubled or tripled in Arizona, and partial shade increased floral abundance in flower crops. The engineering - panel type, mounting height and tilt, structural safety under wind loads, deep-buried armoured cables, smart irrigation and inverter-battery grid architecture - must be tailored to each crop's height and shade tolerance, with shading kept below ~30% for fruit crops and 20-40% for most vegetables and flower crops. Intercultural operations (weeding, mulching, training, pruning, thinning, staking, plant protection) integrate with the array's geometry and microclimate: the AV site is at once an energy plant, a horticultural field and a managed agro-ecosystem.

Limitations of the Review: This review is based on a narrative synthesis of published literature rather than a formal systematic review. The examples are selected to illustrate the diversity of approaches and should not be considered exhaustive. The focus is primarily on peer-reviewed studies from 2019 onwards, but may not capture all relevant research, particularly from non-English sources or grey literature. The economic and policy analyses are based on general observations rather than comprehensive regional assessments. Future work should include systematic reviews, meta-analyses of crop responses, and region-specific economic assessments.

Key Recommendations:

1) **For Researchers**: Conduct systematic meta-analyses of crop responses to shading; develop crop-specific shading threshold models; investigate cultivar variability in shade tolerance; and establish standardised data collection protocols across sites.
2) **For Engineers**: Develop cost-effective elevated mounting structures; optimise panel configurations for crop light requirements; and improve wind-load design codes for tall agri-voltaic structures.
3) **For Policymakers**: Establish clear regulatory frameworks for agrivoltaics; provide subsidies and incentives for dual-use systems; and support research and demonstration projects.
4) **For Farmers**: Start with pilot projects on small areas; select shade-tolerant crops; and seek technical advice on system design and operation.

With continued research, standardised data and capacity building, horticulture-voltaics can deliver climate-adaptive, resource-efficient and energy-positive horticultural systems worldwide.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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