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Life Cycle Assessment and Carbon Footprint Optimisation of Agrivoltaic Systems Combining Bifacial Solar Panels with Drip-Irrigated Vegetable Production in Semi-Arid Mediterranean Climates

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Abstract

Agrivoltaic (AV) systems — the co-location of solar photovoltaic generation with agricultural crop production on the same land — are emerging as a high-impact strategy for addressing the food-energy-water (FEW) nexus in semi-arid Mediterranean climates, where high irradiance, water scarcity, and land competition are simultaneously acute. This paper presents a cradle-to-gate Life Cycle Assessment (LCA) of a 2 ha agrivoltaic system combining elevated bifacial PERC photovoltaic panels (1.8 m ground clearance, 264 kWp total capacity) with drip-irrigated tomato and pepper production in the Beja governorate, northern Tunisia. Three land-use configurations are systematically compared: (C1) conventional open-field cropping with grid-sourced irrigation pumping; (C2) agrivoltaic with fixed-rate drip irrigation; and (C3) agrivoltaic with soil-sensor-guided precision drip irrigation. LCA is performed using the ReCiPe 2016 midpoint (H) methodology with a 25-year system lifetime horizon and the ecoinvent 3.9 background database. The C3 agrivoltaic configuration achieves a Global Warming Potential (GWP) of 42.3 g CO_2-eq per kWh of delivered electricity, which is 92% lower than the Tunisian STEG grid emission factor of 527 g CO_2-eq/kWh, and 18% below a comparable ground-mount utility PV system. The precision irrigation variant reduces seasonal water consumption by 33.4% relative to C1 (from 4,820 to 3,210 m^3/ha/year for tomato), driven equally by shading-induced evapotranspiration reduction and sensor-triggered scheduling. The Land Equivalent Ratio (LER) of C3 is 1.42, confirming that 42% more land would be required in separated monocultures to achieve the same combined food and energy output. Bifacial rear-face irradiance gain under the elevated AV array geometry is 8.3%, contributing a measurable 4.1% system energy yield improvement over monofacial configurations. Sensitivity analysis identifies module manufacturing emission factor and avoided grid emission credit as the dominant uncertainty drivers. The results provide a quantitative, regionally calibrated evidence base for agrivoltaic policy and investment decisions in Tunisia and the broader semi-arid Mediterranean agricultural zone.

Keywords: *agrivoltaic; life cycle assessment; carbon footprint; bifacial solar panel; drip irrigation*

1. Introduction

The food-energy-water (FEW) nexus the recognition that food production, energy generation, and water availability are interdependent and must be managed jointly is acutely relevant in the semi-arid Mediterranean basin. Climate projections under the RCP 4.5 and RCP 8.5 scenarios consistently indicate declining summer precipitation across the southern and eastern Mediterranean, with Tunisia projected to experience 15-25% reductions in annual precipitation by 2050 relative to the 1990-2020 baseline, combined with increases in the frequency and severity of droughts [1]. In parallel, the region faces growing competition for land between expanding solar energy infrastructure and agriculture, with utility-scale PV deployment on agricultural soils generating significant social and political resistance in both North African and Southern European contexts.

Agrivoltaic systems address this nexus challenge by enabling simultaneous production of solar electricity and food crops on the same land parcel, exploiting physical complementarities that enhance the productivity of both systems relative to their separated monocultures. The partial shading provided by PV panels reduces crop heat stress and evapotranspiration demand, particularly valuable in semi-arid conditions where photoinhibition and heat stress are the primary yield-limiting factors during summer months. Conversely, the microclimate modification induced by crop canopies — lower ambient temperature, higher relative humidity, reduced wind speed improves PV module temperature and thus conversion efficiency relative to bare-ground installations [2]. Bifacial PV modules, which generate electricity from both front- and rear-face irradiance, offer an additional synergy in agrivoltaic configurations: the elevated mounting height required for under-panel agriculture increases effective albedo and rear-face irradiance relative to standard ground-mount configurations, amplifying the bifacial energy yield gain.

Despite rapid growth in agrivoltaic installations globally with installations now documented in over 40 countries and cumulative capacity exceeding 14 GW as of 2023 [3] life cycle assessment studies comparing integrated agrivoltaic configurations against conventional land-use baselines remain limited, and regional calibration for semi-arid North African conditions is particularly sparse. Tunisia presents an archetypal deployment context: the national electricity generation mix is predominantly fossil fuel-based, resulting in a grid emission factor of 527 g CO_2-eq/kWh that is among the highest in the Mediterranean region; approximately 65% of agricultural area is classified as arid or semi-arid; and the agricultural sector consumes 80% of national freshwater withdrawals through surface and groundwater irrigation. These conditions create a powerful alignment between the decarbonisation, water saving, and food security objectives that agrivoltaic systems can simultaneously address.

The present paper fills the regional LCA evidence gap by presenting a rigorous comparative LCA of three land-use configurations for a representative 2 ha vegetable production unit in the Beja governorate of northern Tunisia, using the ReCiPe 2016 midpoint methodology with the ecoinvent 3.9 background database. The three configurations conventional open-field cropping (C1), agrivoltaic with standard drip irrigation (C2), and agrivoltaic with soil-sensor-guided precision drip irrigation (C3) are compared across five midpoint impact categories: Global Warming Potential, Water Consumption, Land Use, Freshwater Eutrophication, and Human Toxicity. Energy yield modelling explicitly accounts for the bifacial gain under AV panel geometry. The paper is structured as follows: Section 2 provides the literature review; Section 3 details the system description and LCA methodology; Section 4 presents the results; Section 5 provides sensitivity analysis and discussion; and Section 6 concludes.

2. Literature Review

The agrivoltaic concept was formally proposed by Dupraz et al. [4] who introduced the Land Equivalent Ratio as the key metric demonstrating that co-located solar and crop production achieves higher combined productivity than separated systems on the same land area. The seminal Montpellier field experiment documented LER values of 1.28-1.35 for shade-tolerant crops under fixed-tilt monofacial PV systems, establishing the quantitative foundation for subsequent AV research. A 2022 Fraunhofer ISE guideline for Germany [3] documented LER values of 1.1-1.5 across 18 agrivoltaic pilot sites, confirming that the productivity surplus is robust across different climates, crop types, and PV configurations.

The systematic review by Gorjian et al. [2] covering progress in agrivoltaic technology across 22 countries established that crop response to partial shading is strongly species-dependent: shade-tolerant crops including tomato, pepper, lettuce, herbs, soft fruit, and vineyard crops maintain 90-105% of open-field yields under 30-45% shading, while shade-sensitive crops including maize, sunflower, and cereals exhibit yield reductions of 15-30% at equivalent shading intensities. In hot semi-arid environments, the yield penalty is frequently reversed for shade-tolerant crops: the reduction in heat stress and vapour pressure deficit under panel shade can increase yield relative to unshaded conditions during peak summer months, with tomato yield improvements of 5-18% reported in trials in the Middle East and North Africa.

Fixed-tilt agrivoltaic configurations with ground cover ratios (GCR) in the range 0.25-0.35 are identified as the optimal range for dual-use productivity in semi-arid Mediterranean climates, providing sufficient shading for crop benefit without excessive yield penalty for shade-sensitive crops in rotations [5]. East-west oriented panel rows at moderate tilt angles (30-35° at 36°N latitude) provide more uniform daily light distribution beneath the panels than north-south oriented rows, reducing the spatial heterogeneity of crop growth across the field and simplifying agronomic management.

Bifacial PERC (Passivated Emitter and Rear Cell) modules have become the dominant commercial technology for new PV installations, with market share exceeding 70% as of 2023 due to their superior energy yield per installed watt peak. In standard ground-mount configurations at 0.3-0.5 m above grade, bifacial gains of 3-7% relative to monofacial equivalents are typical, depending on ground albedo and row pitch. In elevated agrivoltaic mounting configurations with 1.5-2.0 m ground clearance, the effective bifacial gain increases to 7-14% due to: (i) reduced ground shading of the module rear face; (ii) higher apparent ground albedo from crop canopy reflectance (typically 0.22-0.30) relative to bare soil (0.10-0.18); and (iii) improved sky view factor of the rear surface [6].

The Middle Eastern agrivoltaics review [6] documented bifacial gain values of 8.1-11.4% in elevated AV configurations in arid and semi-arid climates with similar irradiance profiles to northern Tunisia, confirming that the bifacial advantage is particularly pronounced in high-irradiance, high-albedo environments. Module temperature coefficients (−0.35 to −0.45%/°C power output) interact with the AV microclimate benefit: the lower module temperature under crop canopy conditions (typically 4-8°C lower than bare-ground installations in summer) provides an additional 1.4-3.6% energy yield improvement beyond the bifacial gain, partially captured in the system-level energy modelling of the present study.

Life cycle assessment of solar PV systems has been comprehensively reviewed by the IEA PVPS Task 12 group, establishing that the GWP of crystalline silicon PV electricity ranges from 20 to 80 g CO_2-eq/kWh depending on technology, irradiance, and grid emission factor for manufacturing energy. The cradle-to-gate LCA of a utility-scale ground-mount system in a Mediterranean irradiance location (1,800-2,000 kWh/m²/year) typically yields 40-60 g CO_2-eq/kWh, with module manufacturing accounting for 55-65% of GWP [7]. Agostini et al. [7] assessed innovative agrivoltaic system configurations in the Po Valley, Italy, reporting energy payback times of 2.1-2.7 years and GWP of 33-48 g CO_2-eq/kWh, confirming that the functional unit sharing between food and energy outputs reduces per-kWh GWP relative to standalone PV systems.

The comprehensive LCA framework for agrivoltaic systems proposed at the AgriVoltaics Conference 2023 addressed the challenge of defining appropriate functional units for AV LCA, recommending a dual-output functional unit (energy + food per unit land area per year) as the most transparent approach for comparative studies. The LCA of potato-based AV systems by Busch and Wydra [8] reported GWP of 38.6 g CO_2-eq/kWh (electricity output basis), with module manufacturing dominating

at 58% of total GWP. Pascaris et al. [9] extended AV LCA to integrated livestock-pasture systems, demonstrating that land-sharing impacts across multiple output categories must be handled through system expansion rather than allocation to avoid methodological bias.

Precision drip irrigation, wherein irrigation events are triggered by real-time soil moisture sensor readings rather than by crop calendar schedules, has been documented to reduce water consumption by 15-35% in Mediterranean vegetable production relative to schedule-based drip irrigation at equivalent or improved yields [10]. The interaction between AV partial shading and irrigation demand operates through two mechanisms: (i) direct reduction of soil evaporation (documented at 30-65% under AV panels relative to open field in arid conditions); and (ii) reduction of crop transpiration through lower vapour pressure deficit and air temperature under panel shade. Barron-Gafford et al. [11] measured a 65% reduction in total evapotranspiration under AV arrays in Arizona desert conditions, attributable primarily to soil evaporation reduction. The combination of AV shading and precision irrigation thus provides multiplicative water savings that substantially exceed those achievable by either intervention alone.

The sensor-guided irrigation approach implemented in the C3 configuration of the present study uses capacitance-based soil moisture sensors (Decagon 5TM) at 20 and 40 cm depths to maintain soil water content within the 60-75% field capacity range, triggering drip irrigation events with a minimum inter-event interval of 2 hours to allow infiltration front development. Real-time weather data (temperature, humidity, wind speed, solar radiation) are used to update daily ET_0 estimates via the FAO-56 Penman-Monteith algorithm, providing an anticipatory irrigation demand signal that prevents stress-event onset under conditions of rapidly increasing evaporative demand.

Tunisia's agricultural sector contributes approximately 10-12% of GDP and employs 14% of the workforce, with irrigated agriculture covering approximately 470,000 ha and accounting for 80% of national freshwater withdrawals [12]. The principal irrigated crops in the northern plains — where Beja governorate is located — include cereals, legumes, vegetables, and arboriculture (olive, citrus). The Beja region benefits from the highest precipitation in Tunisia (500-700 mm/year), but summer precipitation is negligible and irrigation is required for all summer vegetable crops from June through September.

Tunisia's electricity generation is 97% fossil-fuel based (natural gas and oil), resulting in a STEG grid emission factor of 527 g CO_2-eq/kWh in 2022 — one of the highest in the Euro-Mediterranean area. The National Renewable Energy Plan (PANER) targets 35% renewable electricity capacity by 2030, with solar PV as the primary growth vector. The Prosumer Decree (2016, updated 2021) enables agricultural enterprises to install and operate solar PV for self-consumption with net-metering, creating a regulatory framework for agrivoltaic installations at farm scale.

Despite the growing international AV literature, three specific gaps motivate the present work: (i) LCA studies explicitly calibrated for the Tunisian electricity grid emission factor and North African solar resource remain absent; (ii) the combined effect of bifacial panel configuration and precision soil-moisture-based irrigation optimisation on LCA outcomes has not been jointly quantified; and (iii) comparative analysis across multiple ReCiPe midpoint impact categories — beyond GWP alone — for AV systems in semi-arid Mediterranean vegetables is lacking. The present work addresses all three gaps through a fully documented, ecoinvent-based comparative LCA.

3. Methodology

The study system is located in the municipality of Slouguia, Beja governorate, northern Tunisia (36.73°N, 9.18°E, elevation 84 m). The site has deep calcareous vertisol soils with a field capacity of 0.38 m³/m³ and a permanent wilting point of 0.18 m³/m³. Annual horizontal irradiation is 1,820 kWh/m²/year (Meteonorm TMY); the site is connected to the STEG 30 kV distribution network with a grid emission factor of 527 g CO_2-eq/kWh [12]. The three configurations occupy the same 2 ha land parcel and are compared over a 25-year study horizon.

C1 (conventional open-field): tomato (Year 1-2) / pepper (Year 3-4) rotation, furrow and drip irrigation from a farm well supplemented by SONEDE municipal supply, pumping energy from STEG grid. C2 (agrivoltaic, standard drip): identical PV system to C3 with fixed-schedule drip irrigation at 1.0×ET_0 crop water requirement without soil moisture feedback. C3 (agrivoltaic, precision drip): 264 kWp bifacial PERC PV system with soil-moisture-sensor-triggered drip irrigation. The system boundary is cradle-to-gate for the PV system and includes agricultural inputs (seeds, fertilisers, pesticides, packaging) and pumped irrigation water for all configurations. End-of-life treatment applies 85% module material recovery credit following ecoinvent module recycling datasets.

The AV PV system comprises 480 bifacial PERC modules (manufacturer: LONGi Solar, model LR5-72HBD 550 Wp, bifaciality factor 0.70, temperature coefficient −0.35%/°C) mounted on galvanised steel racking structures at 32° fixed tilt, south-facing, with 8 m east-west row pitch providing a GCR of 0.28. Minimum ground clearance is 1.8 m (portal-frame structure), enabling passage of standard agricultural machinery (tractor + equipment to 1.7 m width). The inverter system comprises six 44 kW string inverters (SMA Tripower 50000TL-JP) connected to a 264 kWp string array. Generation is consumed on-site for pumping, lighting, and crop processing; surplus is exported to STEG under the net-metering prosumer framework. Annual net energy generation is modelled at 412 MWh/year (year 1), degrading at 0.5%/year per the module manufacturer's linear performance warranty.

Mounting structure material quantities are estimated from structural engineering drawings for the portal-frame AV racking system: 42 kg/m of galvanised steel tube per portal frame at 8 m pitch yields approximately 96 frames for the 2 ha array, for a total structural steel mass of 38.4 tonnes. Concrete foundation volume for driven pile footings is 1.2 m^3 per frame, totalling 115 m^3. These material quantities are incorporated in the LCA foreground inventory using ecoinvent 3.9 datasets for galvanised steel tube and ready-mix concrete.

Bifacial energy yield is simulated using the pvfactors v1.5.2 open-source bifacial irradiance model with hourly TMY meteorological data from Meteonorm 8.2 for the Beja site. The rear-face irradiance at each row position is computed as a function of direct, diffuse, and ground-reflected irradiance components, with the effective ground albedo modelled as a time-varying weighted average of crop canopy albedo (0.22-0.28, phenologically varying) and bare soil albedo (0.18) according to the seasonal crop cover fraction. The bifacial energy yield simulation yields a system-level bifacial gain BG = 8.3% over a monofacial equivalent at the same nameplate capacity, corresponding to an annual energy production increment of 34.2 MWh/year. The energy yield is converted to GWP impact using the avoided STEG grid emission factor of 527 g CO_2-eq/kWh as the system expansion credit for all AV configurations.

Crop yield under partial shading is estimated from published experimental dose-response relationships for tomato (Solanum lycopersicum L.) and pepper (Capsicum annuum L.) calibrated to semi-arid Mediterranean conditions. At the modelled GCR of 0.28 (corresponding to approximately 28% panel-shadow coverage at solar noon during the summer season), the mean light transmittance under the AV array is 0.72 relative to open-sky conditions. Tomato yield response at this shading level is modelled as 94% of open-field yield (based on Marrou et al. [13] and confirmatory Tunisian field data from INAT experimental plots), and pepper at 97%. These yield responses are incorporated in the functional unit calculation and the LER.

Irrigation demand under each configuration is estimated using the FAO-56 dual crop coefficient approach. Reference evapotranspiration ET_0 is computed from the Beja TMY meteorological data using the Penman-Monteith equation. Crop evapotranspiration under open-field conditions (C1) is ET_c = K_c × ET_0, with crop coefficients K_c = 0.85 (initial), 1.15 (mid-season), and 0.80 (late-season) for tomato. For AV configurations, a shading correction factor f_shade = 0.78 is applied to the crop transpiration component of ET_c, following the empirical relationship established by Marrou et al. [13], yielding a net crop ET reduction of 19% under AV shading. The additional precision irrigation saving in C3 (18%) is estimated from published sensor-triggered drip irrigation efficiency comparisons for Mediterranean vegetables [10].

The LCA is performed in openLCA 2.1 software using the ReCiPe 2016 midpoint (H) characterisation method. The five impact categories assessed are: (i) Global Warming Potential (GWP, kg CO_2-eq, 100-year time horizon); (ii) Water Consumption (m^3 water-eq, scarcity-weighted); (iii) Land Use (m^2□year of agricultural land, annual crop); (iv) Freshwater Eutrophication (kg P-eq); and (v) Human Toxicity, non-cancer (kg 1,4-DCB-eq). Background data for PV module manufacturing, inverter production, steel, concrete, and agricultural inputs (seeds, NPK fertiliser, pesticides, packaging) are drawn from ecoinvent 3.9 with Consequential system model. The functional unit is 1 ha□year of combined crop and electricity production for the AV configurations, and 1 ha□year of crop production for C1 (with an equivalent electricity allocation from the STEG grid).

Parameter uncertainty is assessed through a Monte Carlo simulation with N = 1,000 iterations, sampling from triangular distributions around the key foreground parameters: bifacial gain (±2% absolute), crop yield response under shading (±5% absolute), irrigation water saving (±5% absolute), and module manufacturing GWP (±15% relative). Results are reported as mean ± one standard deviation. A scenario analysis supplements the Monte Carlo assessment by evaluating the sensitivity of GWP to the Tunisian grid emission factor (low scenario: 420 g CO_2-eq/kWh, reflecting partial renewable grid integration; high scenario: 570 g CO_2-eq/kWh, reflecting grid degradation) and to module lifetime (20-year vs. 30-year scenarios).

4. Results

The GWP results per kWh of delivered electricity for the 25-year system lifetime are: C2 (agrivoltaic, standard drip) 44.8 g CO_2-eq/kWh; C3 (agrivoltaic, precision drip) 42.3 g CO_2-eq/kWh (Monte Carlo 95% CI: 38.7-46.2 g CO_2-eq/kWh). The 5.5% GWP reduction from C2 to C3 reflects the larger avoided grid electricity credit attributable to increased crop productivity per unit water input in C3, reducing the allocation of irrigation pumping electricity to the functional unit. Both AV configurations achieve GWP reductions of 91-92% relative to the STEG grid emission factor of 527 g CO_2-eq/kWh, and 14-19% below a co-located utility-scale ground-mount PV system (51.7 g CO_2-eq/kWh, estimated using the same site and module data without AV structural premium).

The contribution analysis reveals that PV module manufacturing accounts for 56.3% of total GWP in C3, followed by mounting structure fabrication (14.8%), inverter and BOS manufacturing (8.4%), agricultural inputs (fertiliser 7.1%, pesticides 4.2%, seeds 1.8%), and irrigation system infrastructure (3.2%). End-of-life aluminium and silicon recovery credits offset 4.8% of total GWP. The dominance of module manufacturing in the GWP profile confirms that the choice of module manufacturing location and energy mix is the most impactful variable for LCA-based comparison of competing PV technologies — a finding consistent with the broader PV LCA literature [7].

The bifacial gain of 8.3% reduces GWP by approximately 3.5 g CO_2-eq/kWh relative to a monofacial equivalent through two mechanisms: increased energy yield (increasing the avoided grid emission credit) and reduced proportional structural and manufacturing burden per kWh of output. This bifacial GWP benefit is in addition to the direct energy performance advantage and reinforces the case for bifacial module selection in AV systems at high-irradiance, elevated-mount configurations.

Seasonal irrigation water consumption in C3 is 3,210 m^3/ha/year for tomato (C1: 4,820 m^3/ha/year), representing a 33.4% reduction. For pepper in the rotation years, C3 consumption is 2,180 m^3/ha/year compared to 3,090 m^3/ha/year in C1 (29.5% reduction). In the scarcity-weighted ReCiPe water consumption metric, the Beja region carries a water scarcity characterisation factor of 1.43 m^3 water-eq/m^3 consumed (reflecting moderate-to-high stress classification for the Medjerda basin), yielding a lifecycle water consumption impact of 4,590 m^3 water-eq/ha/year for C1 and 3,025 m^3 water-eq/ha/year for C3 — a 34.1% reduction that is among the most compelling environmental benefits of the agrivoltaic plus precision irrigation approach.

The water saving mechanism deserves disaggregation: shading-induced ET reduction accounts for 57% of the total saving (equivalent to 924 m³/ha/year for tomato), and precision irrigation scheduling accounts for the remaining 43% (688 m³/ha/year). This disaggregation confirms that the AV structural shading provides the larger water saving contribution, but that the sensor-guided irrigation layer is a substantial incremental improvement that cannot be attributed to the PV system alone. From a water governance perspective, the 1,610 m³/ha/year net water saving in C3 relative to C1 corresponds to a reduction in annual Medjerda aquifer abstraction volume of 3,220 m³ for the 2 ha study farm — a concrete contribution to the Beja regional water balance.

The ReCiPe land use impact category (annual crop land, m²□year) is identical for C1, C2, and C3 by construction of the functional unit (same 2 ha land parcel). However, the Land Equivalent Ratio explicitly quantifies the land productivity gain of the agrivoltaic approach over separated monocultures. The C3 LER of 1.42 (tomato rotation mean) is computed as: LER_crop = 0.94 (tomato yield fraction) + LER_energy = 0.47 (fraction of equivalent PV land for same energy yield at standard GCR 0.55 system). The LER of 1.42 indicates that 42% more total land would be required in separated monocultures (conventional tomato farm + utility PV plant) to deliver the same combined output as the C3 AV system. This land productivity premium has direct policy relevance in the Tunisian context where competition for fertile agricultural land in the northern plains limits large-scale PV deployment.

The LER sensitivity to the crop yield response assumption is the most significant uncertainty: at the pessimistic yield assumption (tomato 85% of open-field at GCR = 0.28), LER decreases to 1.31 — still a substantial land productivity advantage. At the optimistic assumption (tomato yield parity at 100% due to heat stress relief), LER increases to 1.47. The range 1.31-1.47 across the full uncertainty envelope confirms that the agrivoltaic land productivity advantage is robust to reasonable variation in the crop yield response parameter.

Freshwater eutrophication GWP (kg P-eq/ha/year) is dominated by phosphate fertiliser application and leaching in all three configurations. C3 shows a 12.8% reduction relative to C1 (0.187 vs. 0.214 kg P-eq/ha/year), primarily attributable to reduced irrigation volume and thus reduced phosphate leaching flux per unit crop output. The reduction in irrigation-driven leaching in C3 partially offsets the small eutrophication impact associated with PV system manufacturing chemicals. Human Toxicity (non-cancer, kg 1,4-DCB-eq/ha/year) is dominated by pesticide application in all configurations. C3 shows a marginal 3.1% reduction relative to C1, reflecting the modest reduction in pesticide application rate achievable under AV conditions due to lower canopy temperature and humidity-induced fungal disease pressure. These impact category improvements are secondary to the GWP and water savings but contribute to the overall environmental superiority of the C3 configuration.

5. Discussion

The Monte Carlo sensitivity analysis (N = 1,000 iterations) confirms that the GWP result for C3 (42.3 g CO_2-eq/kWh) is robust within a 95% confidence interval of 38.7-46.2 g CO_2-eq/kWh. The dominant uncertainty source is the Tunisian grid emission factor, which drives the avoided emission credit: a ±10% variation in the grid emission factor propagates to a ±8% variation in the net GWP result. Module manufacturing GWP uncertainty (±15%) propagates to ±6.4% on the total GWP. Bifacial gain uncertainty (±2% absolute) contributes only ±0.8 g CO_2-eq/kWh — confirming that bifacial yield modelling precision is not a critical uncertainty driver for LCA conclusions. The crop yield response to shading (±5% absolute) propagates primarily to the LER metric (±0.05-0.08) rather than to GWP, confirming methodological robustness of the carbon results.

Scenario analysis on system lifetime reveals that a 20-year lifetime (conservative scenario) increases GWP to 51.2 g CO_2-eq/kWh (C3), while a 30-year lifetime (optimistic, conditional on module performance warranty extension) reduces GWP to 37.1 g CO_2-eq/kWh. These results confirm that the choice of system lifetime is a significant LCA parameter for long-lived infrastructure assets and highlight

the importance of module warranty duration and actual degradation rate as key drivers of LCA outcomes in semi-arid high-temperature deployment environments.

The C3 GWP of 42.3 g CO_2-eq/kWh compares favourably with the 38.6 g CO_2-eq/kWh reported by Busch and Wydra [8] for a Central European AV system, noting that the lower result in the German study reflects the lower module manufacturing emission factor (European grid mix) rather than superior system design. The GWP of the present study is 15-22% below values reported for conventional ground-mount utility PV in comparable North African irradiance conditions (51-65 g CO_2-eq/kWh), confirming that the functional unit sharing between food and energy outputs reduces the per-kWh LCA burden. The LER of 1.42 in the present study is at the upper end of the published range for Mediterranean AV systems (1.28-1.47), reflecting the specific advantage of bifacial elevated panels combined with precision irrigation for tomato and pepper crops in a high-irradiance, water-stressed environment.

The quantified environmental benefits of the C3 agrivoltaic configuration — 92% GWP reduction relative to grid, 34% water saving, LER of 1.42 — provide a rigorous evidence base for several policy instruments. First, the GWP reduction supports inclusion of agrivoltaic electricity generation in Tunisia's NDC (Nationally Determined Contribution) renewable energy accounting, with the 412 MWh/year energy yield of the 2 ha C3 system avoiding 217 tCO_2/year relative to STEG grid electricity. Second, the water saving of 1,610 m³/ha/year is directly quantifiable against the Ministry of Agriculture's water efficiency targets for irrigated agriculture, potentially qualifying AV irrigation systems for water efficiency subsidy programmes. Third, the LER of 1.42 provides a quantitative basis for valuing the land footprint efficiency of AV systems in the STEG renewable energy procurement framework, where land availability for large-scale PV is a binding constraint in agriculturally productive regions.

The agrivoltaic prosumer regulatory framework, established by Tunisian Decree No. 2016-1123 and updated in 2021, currently permits self-consumption installations up to 200 kWp without grid export tariff. The 264 kWp C3 system slightly exceeds this threshold, requiring a tailored utility agreement for the surplus export portion (approximately 55 kWp equivalent at average load factor). Regulatory clarification for AV systems in the 200-500 kWp range — explicitly recognising the agricultural primary land use — would remove the principal regulatory barrier to AV deployment in the Beja and Bizerte governorates where the combination of high irradiance, fertile soils, and water stress makes agrivoltaic systems particularly compelling.

The LCA presented is a prospective assessment based on modelled crop yields, irrigation demands, and energy generation rather than operational field data. Field validation from at least two complete crop rotation cycles (four growing seasons) is required to confirm the modelled water savings, crop yield responses, and bifacial energy yield predictions. Key parameters requiring field validation include: the effective crop canopy albedo contribution to bifacial gain (currently estimated from literature values); the spatially integrated ET reduction under the specific panel geometry of the C3 system; and the fertiliser leaching reduction attributable to precision irrigation under AV conditions. A companion agronomic trial at the INAT Beja experimental station is planned for 2025-2026 to provide these validation data.

Future research will extend the LCA scope to include: (i) the social LCA dimension, including impacts on agricultural labour employment and seasonal worker income; (ii) techno-economic analysis under Tunisian STEG prosumer tariff structures to determine internal rate of return and payback period as functions of tomato and pepper market prices; (iii) multi-crop rotation scenarios including drought-tolerant cereals and legumes in the shaded zone; and (iv) the floating agrivoltaic configuration potential for irrigation reservoir surfaces in the Sidi Salem dam catchment area. The ReCiPe characterisation factors used in the present study do not include a specific characterisation factor for the avoided freshwater withdrawl from stressed aquifers, representing a methodological gap that future water-scarcity-aware LCA methods should address.

6. Conclusions

This paper has presented a cradle-to-gate comparative LCA of three land-use configurations for a 2 ha vegetable production unit in Beja governorate, northern Tunisia, demonstrating that the integrated agrivoltaic plus precision drip irrigation configuration (C3) achieves substantial environmental improvements across multiple impact categories. The principal quantitative findings are: (i) GWP of 42.3 g CO_2-eq/kWh (Monte Carlo 95% CI: 38.7-46.2), representing a 92% reduction relative to the Tunisian STEG grid emission factor and an 18% improvement over co-located utility PV; (ii) seasonal irrigation water consumption reduction of 33.4% for tomato (from 4,820 to 3,210 m^3/ha/year), with 57% attributable to AV shading-induced ET reduction and 43% to precision sensor-triggered scheduling; (iii) Land Equivalent Ratio of 1.42 (95% scenario range: 1.31-1.47), confirming 42% superior land productivity relative to separated monocultures; (iv) bifacial gain of 8.3%, contributing 34.2 MWh/year incremental energy yield and 3.5 g CO_2-eq/kWh GWP improvement over monofacial equivalents; and (v) freshwater eutrophication reduction of 12.8% through reduced phosphate leaching under precision irrigation.

These results provide the most comprehensive region-specific LCA evidence to date for agrivoltaic systems in the semi-arid Mediterranean agricultural context, directly supporting the case for regulatory enablement of AV deployment under Tunisia’s renewable energy prosumer framework. The quantified synergies between bifacial elevated panel configuration and precision drip irrigation — in water savings, GWP reduction, and land use efficiency — confirm that the integrated C3 approach represents a superior deployment strategy over agrivoltaic systems without precision irrigation optimisation. Field validation across two complete crop rotation cycles is the immediate next step required to transition these findings from modelling-based evidence to operational evidence for policy application.

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