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Soilless Agriculture Integrated With Agrivoltaics: A Pathway To Sustainable Food And Energy Security In India

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Abstract. This paper investigates the integration of agrivoltaics with soilless cultivation for Indian smallholder farmers. It reviews India's agricultural challenges, including climate risks, fragmented holdings, and resource constraints. It then evaluates soilless agriculture's resource efficiency, profitability, and energy needs, highlighting agrivoltaics as a sustainable power solution. Technical synergies, such as energy load matching and digital innovations (real-time sensors, AI crop monitoring, and digital twins), are discussed. Policy recommendations, financial mechanisms, and regulatory guidelines, drawing lessons from successful implementations in China, the U.S., and other regions, are presented to support equitable adoption. The paper concludes by proposing a replicable, integrated model for sustainable agriculture suited to diverse agro-climatic and socio-economic contexts.

Keywords: Agrivoltaics, Digital Twin, Just Transition, Soilless Agriculture

1. Introduction

Ensuring adequate food supply for a global population projected to reach 9.8 billion by 2050 is challenging, especially as arable land per capita shrinks to one-third of its 1970 level and climate uncertainties increase [1][2]. India exemplifies these challenges, with fragmented landholdings, erratic monsoons, and limited resources already constraining agricultural productivity and farmer incomes [3]. Incremental improvements alone are insufficient, emphasizing the need for transformative solutions.

Soilless cultivation dramatically reduces water use, eliminates soil-borne diseases, and boosts yields, but its intensive energy requirements if fossil-fueled could offset sustainability gains [4]. Agrivoltaics, integrating solar photovoltaic (PV) systems into farming, provides clean on-site energy, reduces emissions, and enhances land productivity [5][6][7][8][9]. Drawing on supportive policy lessons from China and the U.S. [10][11], this paper investigates whether agrivoltaic-soilless integration can improve Indian smallholder livelihoods, bolster food and energy security, and proposes region-specific policy and equity strategies for an inclusive agricultural transition.

2. India’s Current Agricultural Realities

2.1 Fragmented Landholdings and Limited Scale

India’s agricultural sector covers approximately 60% of the country’s land area, yet structural constraints severely hinder productivity and profitability. Over 70% of rural households cultivate on farms smaller than one hectare, with median farm sizes often below that threshold [12]. This extreme fragmentation limits economies of scale and traps many smallholders in subsistence-level production. Yields frequently barely exceed household requirements, leaving little surplus for income.

Reliance on monsoon rainfall further heightens vulnerability to weather variability, and suboptimal cropping choices exacerbate resource stress. For instance, cultivating water-intensive crops like rice in semi-arid regions (e.g. parts of Telangana) can intensify local water scarcity and erode long-term sustainability of the land and water resources [3].

2.2 Infrastructure and Policy Gaps

Weak rural infrastructure compounds these challenges. Unreliable electricity supply, inadequate irrigation facilities, and insufficient storage and processing lead to significant post-harvest losses. The lack of cold chain systems causes perishable produce to spoil, and limited avenues for value addition mean farmers cannot easily improve their earnings. Consequently, many smallholders face chronically low and unstable incomes, often prompting seasonal migration to cities in search of work [1].

Certain well intentioned policies can also have unintended effects on innovation. For example, the Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA), which focuses on providing rural employment through manual labor, may inadvertently discourage mechanization or technological adoption on farms [13][3]. Moreover, distorted incentives such as subsidized electricity and water, and insufficient rewards for conservation perpetuate inefficient resource use and marginal returns [3]. These policy and infrastructure gaps underscore the need for new approaches that can break the cycle of low productivity and poverty in India’s agrarian communities.

3. Climate Imperatives for Agricultural Transition

3.1 Projected Climate Changes for India

Recent climate projections for India underscore the urgency of rethinking conventional open field farming. According to the latest CMIP6 model ensembles, monsoon-season (June-September) rainfall is projected to intensify by approximately +15% under a low-emissions pathway (SSP1-2.6) and by around +25% under a high-emissions scenario (SSP5-8.5) by the late 21st century, accompanied by an increase in the number of rainy days. Concurrently, post-monsoon (October-November) average daily temperatures could rise by ~5% under SSP1-2.6 and by ~12% under SSP5-8.5, depending on emissions levels. These shifts indicate heightened climate volatility marked by more frequent extreme rainfall events and prolonged heat stress during critical crop growth windows.

Crucially, such climatic changes are expected to depress crop yields. Nationwide rice yields by 2100 are projected to fall by approximately 3% under SSP1-2.6 and by up to 22% under SSP5-8.5, relative to late 20th-century baselines. In the worst-affected districts, productivity losses could reach one-third under the high emissions scenario. Notably, all Indian districts are expected to experience some degree of rice yield decline under SSP5-8.5. This scenario reflects a broader pattern where traditional monsoon reliant agriculture becomes increasingly untenable [14].

Table 1. *Climate projections for India (2081-2100) and potential rice yield impacts under low and high emission scenarios*

Indicator (Change vs. 1995-2014)	Sustainable Pathway (SSP1-2.6)	Worst-Case Pathway (SSP5 -8.5)
Monsoon Season (JJAS)	15%	25%
Monsoon Wet Days (JJAS)	13%	16%
Post-Monsoon Avg temperature (ON)	5%	12%
Rice Yield Change by 2100	~-3% (avg), +3% to -12% range	~-22%(avg), -11% to -34% range

Taken together, the evidence presents a compelling case for transitioning away from open field farming models that are acutely vulnerable to erratic weather patterns. Heavier downpours, delayed or shortened rainy seasons, and elevated temperatures threaten to destabilize crop development and reduce yields. These systemic risks point to the need for resilient agricultural models that decouple crop growth from direct weather exposure.

Chief among these are controlled-environment systems such as hydroponics and vertical farms and agrivoltaic configurations that co-locate food production with solar infrastructure. These integrated systems can shield crops from climatic extremes while providing clean energy to maintain ideal growing conditions year round. The climate data thus reinforces the central thesis of this paper: that India’s food and livelihood security increasingly depends on adopting technologies that insulate smallholder production from environmental volatility while optimizing land and energy use.

4. Unlocking the Potential of Soilless Cultivation

4.1 Yield, Water Efficiency, and Energy Demand

Hydroponic systems have demonstrated remarkable gains in resource use efficiency compared to conventional soil-based agriculture. In a benchmark study conducted in Arizona, lettuce grown under field conditions yielded approximately 3.9 kg/m²/year, requiring 965 L/m² per crop cycle (~250 L/kg of lettuce). By contrast, hydroponic cultivation yielded about 41 kg/m² while reducing water use to just 20 L/kg. This tenfold increase in productivity is largely due to the use of recirculating nutrient solutions, which minimize water loss through runoff and evaporation. Such efficiency gains are particularly relevant in regions facing freshwater constraints; however, similar studies are needed for a wider variety of crops to evaluate broader applicability [4].

These benefits, however, come with trade-offs particularly in terms of energy use. Hydroponic systems require a steady supply of power for lighting, climate control, and water circulation. The same Arizona study reported an energy input of approximately 90,000 kJ/kg/year for hydroponic lettuce, as opposed to ~1,100 kJ/kg/year in conventional field systems [4]. This high energy demand underscores the need for integrated renewable energy solutions, such as agrivoltaics, to make hydroponics more sustainable and scalable.

4.2 Profitability and Investment Performance

Empirical evidence from India suggests cautious optimism regarding the financial sustainability of hydroponic farming. A recent study analyzed 23 hydroponic farms around Bengaluru, spanning small (~5,000 sq ft) to large (~2-acre) operations. All surveyed farms demonstrated financial viability over a 10-year horizon, with positive net present value (NPV), benefit-cost (B:C) ratios above 1, and internal rates of return (IRR) exceeding the standard 10.5% investment hurdle rate.

Table 2. *Hydroponic farm financials (10-yr) near Bengaluru [15].*

Farm Size (approx.)	NPV@10.5% Discount	B:C Ratio	IRR (%)
large(~2 acres)	23 Million	1.28	19%
Medium (~1 acre)	15.4 Million	1.77	30%
Small-Medium (~0.5 acre)	6.7 Million	1.34	19%
Small (~0.25 acre)	4 Million	1.25	17%
Micro (~0.1 acre)	2.2 Million	1.21	16%

Among the observed scales, one-acre farms achieved the most favorable balance between investment and return. These mid-sized operations combined manageable input costs with high output volumes, resulting in superior B:C and IRR metrics. Larger farms produced higher total profits but experienced slightly lower proportional returns, likely due to greater capital requirements and limits in market absorption for premium produce [15]. Hydroponics thus offers a scalable and adaptable model. Even small operations surpassed profitability thresholds, while the ability to cultivate high value crops like lettuce and herbs year round enhances income stability. These characteristics position hydroponics as a viable option for Indian smallholders aiming for resilient and high return agricultural systems.

5. Integrating Renewable Energy: Agrivoltaics as a Sustainable Solution

5.1 Technical Synergies: Solar Energy in Controlled Environments

Agrivoltaics offers a means to address the substantial energy demands of controlled environment agriculture (CEA) by co-locating photovoltaic (PV) systems with greenhouse and hydroponic facilities. In a hydroponic lettuce greenhouse equipped with a 1kWp PV-battery system, the array covered 58.0 % of the energy required for root zone temperature control in spring, 83.3 % in summer, but only 9.6 % in winter due to limited solar irradiation [5]. For instance, a compact hydroponic smart farm integrating a 300 W fixed-tilt PV array and a Savonius type vertical-axis wind turbine generated an average 1.06 kWh day^{-1} against a consumption of 0.40 kWh day^{-1}, enabling approximately 2.5 days of autonomous operation without external power [7].

Measured via the Land Equivalent Ratio (LER), dual-use agrivoltaic farms often outperform conventional single-use farms in total output (food + electricity) [12]. In addition to land-use benefits United States (Arizona) - Studies found that placing solar panels over crops (including hydroponically grown varieties) lowers evapotranspiration losses and in some cases even enhances crop yields thanks to the moderated microclimate. India (Junagadh Agricultural

University) - Crop yields were ~15% higher under agrivoltaic panels than in open-field plots, due to reduced heat stress and improved water-use efficiency [24].

5.2 Load Matching and Energy Optimization

CEA facilities can be sized so that on-site renewables meet most of their load: modelling of an agrotunnel vertical farm equipped with a 41-48 kW PV array showed that the system achieved net-zero electricity across six temperate climates, with annual self-consumption and self-sufficiency of 32-40 %; self-consumption peaked in winter, while self-sufficiency peaked in summer as loads shifted with solar availability [6]. In addition, deliberate load scheduling- running supplemental lighting, water circulation and HVAC during periods of peak solar output and smart energy management systems can align the majority of electricity consumption with daytime solar production.

5.3 Operational and Strategic Implications for Smallholders

Integrating PV into hydroponic or vertical farms not only trims energy costs but measurably raises farm income. Techno-economic analysis of stilt-mounted agrivoltaic arrays showed that a full-density (FD) layout lifted total farm revenue (crops + solar electricity) by about 30%, while a half-density (HD) design delivered an 8% gain with negligible yield loss. Extrapolating the concept to the current U.S. lettuce acreage suggests it could host an additional 40-77 GW of PV capacity without displacing food production, underscoring the dual economic and energy value of renewable integrated CEA [16].

While direct income from energy sales may vary based on regional tariffs and metering policies, the capacity to offset input costs and ensure power reliability presents a significant strategic advantage. In areas with unreliable grid access or rising diesel costs, on-farm energy autonomy enables year round operation with minimal production risk. Additionally, surplus solar electricity can be redirected to power ancillary farm functions such as cold storage or irrigation pumps, further enhancing resource efficiency. By reducing exposure to fluctuating energy prices and improving operational predictability, renewable integrated systems provide a more stable foundation for long-term smallholder productivity.

6. Emerging Digital Technologies in Soilless Agrivoltaic Systems

6.1 Real-Time Nutrient and Environmental Monitoring

Modern soilless farms use networks of sensors to continuously monitor nutrient solutions and environmental conditions. Ion-selective probes and conductivity/pH sensors can feed real-time data on key nutrients (e.g. nitrate, potassium) into control systems. Likewise, arrays of IoT sensors track climate variables (temperature, humidity, CO_2) and light levels. This continuous feedback enables automated loops: if a nutrient begins to run low or a parameter drifts, pumps and dosing systems adjust immediately. In effect, the system implements precision fertilization and irrigation applying water or nutrients only as needed which greatly reduces waste. For smallholders, such closed-loop monitoring means higher consistency and big savings in labor and inputs, since the system "learns" optimal conditions and maintains them without constant human intervention [17, 18, 25, 26].

6.2 AI and Imaging Tools for Crop Monitoring and Optimization

Advances in artificial intelligence (AI) and imaging technologies are enabling real-time, non-destructive monitoring of crop health and growth in controlled-environment agrivoltaic systems. These tools combine RGB-D (color + depth) cameras with deep-learning models to estimate traits like biomass, leaf area, and stress indicators from plant images [17, 19]. In one benchmark study, a convolutional neural network trained on overhead images of lettuce predicted plant biomass with a mean error of just 7.3 %, even under conditions of leaf overlap and without manual image labelling [17].

Beyond passive monitoring, these systems support predictive and prescriptive management. Changes in growth rate can be flagged as early indicators of water or nutrient stress, triggering real-time alerts for farmer intervention. Some models can invert the observed data to recommend corrective actions such as adjusting fertilizer delivery in response to predicted nitrogen deficiency [17, 19]. In the field, such AI driven tools can be integrated with tractor or drone mounted cameras for large-scale deployment. Yield forecasting models, trained on diverse imagery datasets, have reached average precision scores up to 31-36 % at IoU 0.5 for grape-bunch detection with only tens of labelled images, replacing labour intensive manual surveys and allowing more precise harvest planning [20]. When integrated into agrivoltaic systems, AI-based monitoring also supports optimal use of solar modulated environments by adjusting input schedules (lighting, irrigation, ventilation) to reflect real-time plant needs. This not only boosts productivity and reduces resource waste but also ensures stability in climate sensitive, energy-constrained smallholder contexts.

6.3 Digital Twin Frameworks for Controlled-Environment Optimization

Digital twins create a virtual copy of the agrivoltaic setup to enable “what-if” testing and optimization. In a recent study, a physics-based digital twin was built for an indoor “pod” farm, using ray-tracing to simulate how LED walls illuminate crops [21]. By modeling thousands of lighting configurations (varying LED positions, spectra and geometry) and scoring plant light absorption, the system automatically found the optimal design that maximizes crop power intake for minimal energy use [21]. Such models run quickly on ordinary computers, making them accessible even to small scale operators. More broadly, digital twins can embed crop growth models that predict yield from weather, panel shading, and irrigation schedules. For example, a twin of an agrivoltaic greenhouse could simulate how shifting a PV panel tilt affects under canopy temperature and plant growth. Farmers could then virtually test new layouts or watering regimes without real-world trial and error. By integrating real sensor feeds into the model, the twin stays in sync with actual conditions. In effect, digital twins act like farm simulators: they help plan and automate management, improving resilience. Indian smallholders could use these tools to fine tune system design (e.g. panel spacing, irrigation timing) and adapt technology to local scales before investing in hardware.

7. Institutional Frameworks and Global Insights

7.1 Enabling Environment: Policy and Finance

India has taken initial steps toward clean energy in agriculture through schemes like PM-KUSUM [12], which subsidizes solar-powered irrigation pumps. However, no explicit policies currently promote agrivoltaic installations or soilless cultivation systems. Expanding existing programs to incentivize these integrated approaches could significantly accelerate India’s shift toward energy-sustainable farming. Such policy revisions would directly support smallholder incomes while also advancing environmental objectives.

Financial incentives are crucial to overcome the high upfront costs of agrivoltaic-soilless systems. Key measures include capital subsidies for solar infrastructure, soft loans, and feed-in tariffs to guarantee favorable rates for any surplus solar power fed into the grid. Ensuring a reliable buyback price for excess electricity gives farmers a stable revenue stream, encouraging broader participation. Additional instruments like carbon credits and green bonds can mobilize climate finance to regions where capital is scarce, making it easier to fund projects. Importantly, streamlining administrative procedures (for example, providing a single-window clearance for all required permits) would speed up implementation and reduce bureaucratic hurdles [22].

7.2 Regulatory Clarity, Safeguards, and Region-Specific Guidelines

Clear, crop-first regulations are vital for agrivoltaics. Taiwan's unregulated boom triggered conflicts when panels crowded out farming, proving that safeguards are necessary [12]. Japan avoids this by requiring agrivoltaic sites to deliver at least 80 % of normal crop yield [23], while France classifies energy as a secondary use, so farming stays dominant [12]. India can draw on these lessons by capping allowable shading, setting minimum-yield targets, and prescribing panel height and spacing to ensure solar arrays complement rather than displace agriculture.

Given India's diverse agro-climatic zones, a one-size-fits-all policy for agrivoltaics is unlikely to succeed. Region-specific guidelines are needed. In semi-arid areas, agrivoltaic designs might favor widely spaced panels that provide partial shade suited for drought-tolerant crops. By contrast, regions with high year-round solar irradiance could support denser panel arrangements or the use of spectrum-selective PV technologies to maximize energy generation without overwhelming crops with shade. Tailoring incentives and technical protocols on a state-by-state basis will ensure policies remain relevant locally, boost adoption in different regions, and optimize agrivoltaic performance under varying conditions [12].

7.3 Inclusive Growth and a "Just Transition"

A cornerstone of sustainable agricultural policy is equity. Integrating soilless agriculture with agrivoltaics must explicitly aim to uplift smallholder and marginal farmers, so as not to deepen existing inequalities [11,12,22]. This requires targeted support for those who are resource-poor or lack technical knowledge. For example, training programs can be offered in nutrient solution management, PV system maintenance, and general operational skills to enable smallholders to adopt these innovations. Financial assistance or microloans may be needed to help them cover initial costs. Moreover, working closely with local research institutions, NGOs, and farmer cooperatives can ensure that agrivoltaic-soilless systems are adapted to community needs. By embedding these innovations into holistic rural development plans rather than imposing external solutions, policymakers can encourage community buy-in and equitable distribution of benefits.

7.4 Global Lessons: China and the U.S.

Between 1992 and 2012, China used Township, Village Enterprises, and Special Economic Zones to shift nearly half its farm workforce into higher-productivity jobs, easing land pressure and rural poverty [10]. This policy mix credit access, training, and labour mobility offers a model for freeing labour and capital for modern agri-tech. In the United States, agrivoltaics has followed a similar policy driven path: grants, tax breaks, feed-in tariffs, carbon credits, and long term power-purchase agreements have turned pilot projects into a mature rural-development tool, creating jobs in panel installation and precision-ag tech, adding farm revenue through dual crop and power sales, and boosting land value by rewarding dual use [11].

8. Conclusion

Integrating soilless cultivation with agrivoltaics, informed by global insights and supported by inclusive policies and digital innovations, charts a compelling trajectory for Indian agriculture. This holistic approach harmonizes resource efficiency, renewable energy generation, socio-economic upliftment, and climate resilience. Building on existing policy frameworks, investing in research, and ensuring equitable benefit distribution can enable India to exemplify a sustainable, inclusive model that meets the dual imperatives of food security and environmental stewardship. It stands as a replicable blueprint for other regions striving to balance productivity, sustainability, and social justice in a rapidly changing world.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

Author Contributions

Carthikswami Sunil Thoniparambil: conceptualization (lead); data curation (lead); visualization (lead); writing - original draft preparation (lead); writing - review and editing (equal). Arunkumar Vaidyanathan: writing - original draft preparation (supporting); writing - review and editing (equal).

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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