Working Draft #1

Placeholder Name of the conference

Placeholder Session title

https://doi.org/10.52825/xxxx........ DOI placeholder (WILL BE FILLED IN BY TIB Open Publishing)

© Authors. This work is licensed under a [Creative Commons Attribution 4.0 International License](https://creativecommons.org/licenses/by/4.0/)

Published: (WILL BE FILLED IN BY TIB Open Publishing)

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

Subtitle

First Author1 https://orcid.org/0000-1111-2222-3333, Second Author2 https://orcid.org/0000-2222-333-4444, and Third Author3 https://orcid.org/0000-1111-3333-4444

1 University College London, UK

2 TIB Open Publishing, Germany

3 Technische Hochschule Wildau, Germany

\*Correspondence: Author Name, mail@email.de

**Abstract.** The abstract should summarize the contents of the paper in short terms, i.e. in up to 250 words. Please capitalize all major words in the title/heading, including the second part of hyphenated major words (e.g., Self-Report not Self-report). Please also capitalize all words of four letters or more. Please capitalize the keywords.

**Keywords:** First Keyword, Second Keyword, Third Keyword

# 1. Abstract

As global population growth intensifies the demand for food [1], traditional agricultural systems—constrained by diminishing arable land, climate variability, and water scarcity—must adapt to ensure future food security. In India, where small landholdings and monsoon-dependent cropping intensify inefficiencies, conventional farming struggles to deliver stable yields and sustainable incomes [2]. This paper advocates a paradigm shift to soilless agriculture methods—such as hydroponics [3]—that significantly improve resource efficiency and productivity. However, these approaches, while easing pressures on land and water, require higher energy inputs that can burden national grids and offset environmental gains.

Integrating agrivoltaics—co-locating solar photovoltaic panels with crop production—addresses this energy challenge [4]. By harnessing abundant solar irradiance, agrivoltaics can power soilless systems sustainably, reduce operational costs, and moderate local microclimates to enhance crop outcomes. Drawing on global experiences, including China’s policy-driven shifts to uplift rural livelihoods and U.S. demonstrations of agrivoltaics’ potential to boost employment and land-use efficiency [5,6], this paper outlines the technical, economic, and policy frameworks needed to adopt agrivoltaics in India. It emphasizes supportive incentives, regulatory clarity, capacity building, and a “Just Transition” framework to ensure equitable, inclusive growth.

Ultimately, integrating soilless agriculture and agrivoltaics represents a strategic convergence of food production and renewable energy generation. Such a transformation promises to revitalize Indian agriculture—improving yields, strengthening rural incomes, and advancing national sustainability goals—while providing a replicable model for other countries facing similar challenges.

# 2. Introduction

Feeding a global population expected to approach 9.8 billion by 2050 ranks among the most urgent and complex challenges of our time [1]. As the world strives to increase food production, it must contend with rapidly declining arable land per capita—projected to be just one-third of its 1970 level by mid-century—and the compounding stresses of climate change, water scarcity, and expanding drylands [7,8]. Meeting these intensifying demands for food, while maintaining environmental integrity and ensuring equitable access to resources, requires more than incremental improvements to traditional farming methods. It calls for a paradigm shift that reimagines agriculture in a resource-constrained, climate-unstable era.

This imperative is not purely technical; it is deeply rooted in social and economic systems. Persistent food insecurity in regions like Africa and the vulnerability of farming communities worldwide underscore the interdependence of agriculture, rural livelihoods, and global stability [1]. Many countries face structural and environmental hurdles that limit the potential of conventional soil-based farming. India, with its immense agricultural footprint and diverse ecological zones, exemplifies these strains, facing intricate challenges that will be examined more closely in the following section. Without transformative interventions, these conditions could restrict India’s ability to meet future dietary needs or adapt to shifting environmental conditions.

Among the promising innovations poised to transcend these barriers are soilless cultivation methods—hydroponics, aeroponics, and aquaponics—that can substantially reduce water usage, eliminate soil-borne diseases, and enable high-yield, controlled-environment production [3,9]. Yet, while these methods conserve critical resources and improve productivity, they often demand higher and more reliable energy inputs for lighting, nutrient delivery, and environmental management [7,10]. If powered by fossil fuels, this intensification risks offsetting the very sustainability gains soilless systems aim to deliver.

It is here that agrivoltaics—the integration of photovoltaic (PV) solar systems into agricultural landscapes—emerges as a complementary solution. By supplying clean, locally generated energy, agrivoltaics can decarbonize soilless cultivation, reduce operational costs, and leverage land more efficiently. Lessons gleaned from global experiences, including policy-driven rural transformations in China and agrivoltaic advancements in the United States, provide valuable insights into how strategic governance, technological adoption, and economic incentives can align to foster a new agricultural paradigm [1,4,10,11,12].

This paper builds on these insights to chart a sustainable and inclusive trajectory for Indian agriculture. After detailing India’s current agricultural realities, it will highlight the rationale for adopting soilless methods, examine how agrivoltaics addresses key energy and environmental challenges, and recommend policy frameworks and technological pathways. It will also emphasize the importance of a “Just Transition,” ensuring that these innovations do not exacerbate inequalities. Ultimately, the aim is to guide India toward an agricultural future that harmonizes food security, renewable energy, socio-economic upliftment, and environmental stewardship, setting a precedent for other nations facing comparable challenges.

# 3. India’s Current Agricultural Realities

India’s agricultural landscape is distinguished not only by its scale—about 60% of the land is under cultivation—but also by profound structural and environmental constraints. More than 70% of rural households manage farms smaller than one hectare, with the median even lower, severely limiting economies of scale and profitability [13]. These fragmented holdings often force smallholders into subsistence-level farming, where yields barely cover household consumption. Reliance on monsoon rains leaves production vulnerable to erratic weather, while prevalent crop choices frequently mismatch local agro-climatic conditions. For example, cultivating high-water-demand staples like rice in semi-arid regions, such as parts of Telangana, exacerbates water scarcity and undermines long-term resource sustainability [2].

Weak rural infrastructure compounds these challenges. Many farmers lack reliable electricity, irrigation facilities, and post-harvest storage options. Without adequate cold-chain systems, wastage remains high, and the absence of effective processing or value-added activities means rural communities miss opportunities to retain income from agriculture. Under these conditions, smallholder incomes remain both low and unstable, driving seasonal migration into cities and contributing to urban pressures [13,8]. Furthermore, policies aimed at employment generation—like the Mahatma Gandhi National Rural Employment Guarantee Act (MNREGA)—while noble in intent, may inadvertently discourage mechanization and innovation by prioritizing manual labor over efficiency gains. This policy environment, combined with input distortions (e.g., subsidized electricity and water) and a lack of incentives for adopting more sustainable practices, perpetuates a cycle of marginal returns and suboptimal resource use [14].

# 4. Detailed Comparison of Hydroponic vs. Conventional Lettuce Production

Empirical evidence from controlled studies underscores the quantitative advantages soilless systems can offer over conventional agriculture in terms of yield, water use, and spatial efficiency. A landmark comparison conducted in Arizona, focusing on lettuce production, provides a concrete illustration of these differences. Under traditional field conditions, lettuce yields averaged around 3.9 kg/m²/year with water requirements approximating 965 L/m² per crop cycle (or about 250 L/kg of lettuce) [5]. By contrast, the hydroponic setup achieved an annual yield of 41 kg/m²—over ten times higher—while reducing water usage to just 20 L/kg of produce [5]. This efficiency stems from the direct and continuous delivery of nutrients to the roots, eliminating variability associated with soil fertility and irrigation inefficiencies. Rather than losing significant water to runoff and evaporation, as in open-field farming, the recirculating nutrient solutions in hydroponics retain and reuse water more effectively [5].

Such dramatic improvements in resource use efficiency are critically important as global demands for food intensify and fresh water supplies face mounting stress. However, the Arizona study also highlights a pivotal challenge: energy consumption. Maintaining optimal conditions in a soilless environment requires continuous operation of lighting (often supplemented to ensure consistent photosynthetic activity), climate control, and water pumps [5]. The lettuce study quantified this difference starkly—hydroponic production demanded about 90,000 kJ/kg/year, dwarfing the 1,100 kJ/kg/year consumed in conventional fields [5]. While controlled environments can stabilize yields and enhance overall productivity, they impose an energy footprint that, if met primarily by fossil-fuel-based grids, can offset environmental gains from efficient water use and high yields.

This tension between resource efficiency and elevated energy requirements suggests that the sustainability of soilless methods cannot be assessed in isolation. Integrating renewable energy sources, particularly solar power through agrivoltaics, emerges as a strategic approach to reconciling these trade-offs [4]. Solar panels, installed above or adjacent to soilless cultivation areas, can supply clean electricity to power pumps, lighting arrays, and climate control systems [4]. In doing so, agrivoltaics can curb greenhouse gas emissions, reduce operational costs in the long term, and stabilize energy inputs against grid uncertainties [4].

The Arizona lettuce case thus serves as more than just a single-crop comparison; it exemplifies the fundamental challenge facing the widespread adoption of soilless agriculture. While the agronomic and water-use benefits are clear and substantial, scaling these systems sustainably hinges on addressing their energy intensity [5]. Agrivoltaics provides a pathway to harmonize productivity gains with environmental stewardship. By pairing high-yield, water-efficient soilless systems with renewable energy solutions, producers can achieve a model of agriculture that leverages precision growing techniques without incurring an untenable carbon footprint [4].

In essence, the data-driven insights from field-to-hydroponic comparisons underscore both the promise and the complexity of transitioning to soilless agriculture at scale. The next logical steps involve not only refining these production systems for broader crop varieties and conditions but also ensuring that their energy demands are met through sustainable and regionally appropriate renewables [4]. This integrated approach offers a blueprint for agricultural innovation that is as attuned to environmental limits as it is committed to fulfilling the world’s food needs [5,4,9].

# 5. Integrating Renewable Energy: Agrivoltaics as a Sustainable Solution

As soilless systems mature and demonstrate their capacity for higher yields and water savings, the energy intensity of these production methods emerges as a defining challenge. Meeting continuous demands for water pumping, climate regulation, and artificial lighting without undermining environmental gains requires a pivot toward clean, reliable energy sources. Here, agrivoltaics—integrating photovoltaic (PV) panels within the agricultural landscape—provides this critical link.

By mounting solar panels above or alongside crops, agrivoltaics leverages the same land area to produce both food and electricity, optimizing overall resource use [5]. This dual-purpose approach is evaluated using the Land Equivalent Ratio (LER), which compares combined outputs of food and energy from the same plot to what would be obtained if each was produced independently. An LER greater than one indicates more efficient land utilization, highlighting agrivoltaics’ potential to enhance productivity without expanding the agricultural footprint [8,9]. Importantly, soilless agriculture stands to benefit disproportionately from this synergy: the stable, nutrient-controlled environments of these systems can operate year-round, and integrating solar panels ensures that they draw on renewable power rather than carbon-intensive grid electricity.

Beyond supplying clean energy, strategically positioned solar panels can positively influence the microclimate beneath them. Partially shading crops reduces temperature extremes, mitigates water evaporation, and can stabilize conditions that soilless systems depend on for consistent, high-quality yields [15,9]. These moderated conditions have tangible benefits. At Junagadh Agricultural University (JAU) in India, agrivoltaic setups delivered approximately 15% higher crop output compared to open-field conditions, attributed partly to reduced heat stress and improved water-use efficiency [16]. Similarly, studies in Arizona have shown that integrating solar panels with crops, including those grown hydroponically, can increase yields and enhance water use efficiency by creating more favorable growing conditions and reducing evapotranspiration losses [5,10]. In Italy, agrivoltaic lettuce production under semi-transparent PV panels maintained yields comparable to open-field cultivation while generating substantial electricity, effectively neutralizing trade-offs and demonstrating that agrivoltaics can preserve or enhance agricultural output [19].

Equally significant is the economic dimension. Farmers adopting agrivoltaics gain a secondary revenue stream from electricity generation, offsetting operational costs and stabilizing incomes—an especially important consideration for smallholders who often struggle to absorb financial risks. When applied to soilless agriculture, this energy-income synergy reduces the burden of expensive inputs like LED lighting and climate control systems, making high-tech cultivation more accessible over time [9,14]. Such diversification of farmer income can also insulate rural households from price volatility in food markets and uncertainty in traditional cropping patterns.

In essence, agrivoltaics addresses the central tension identified previously: while soilless systems excel at maximizing resource efficiency and yields, they are heavily dependent on stable, often substantial, energy inputs. Agrivoltaics directly tackles this concern by supplying green energy onsite, diminishing reliance on conventional grids, and cutting greenhouse gas emissions. By achieving both horticultural and electrical outputs, it transforms farmland into multifunctional production spaces aligned with principles of sustainability, resilience, and economic opportunity.

As agrivoltaic technologies advance—through innovations like semi-transparent or spectrum-selective PV materials that fine-tune light quality for optimal photosynthesis—the integration with soilless agriculture can become even more seamless [8,19,20]. This evolving synergy points to a future where agriculture is not limited by soil fertility, water availability, or energy costs. Instead, it can thrive at the intersection of biological precision and renewable power, offering a compelling roadmap for scaling sustainable food production in a warming, resource-constrained world.

# 6. Institutional Frameworks, and Economic Viability

Realizing the full potential of soilless agriculture integrated with agrivoltaics requires not only technological advances but also robust, well-structured policy frameworks. In India, existing initiatives like the PM-KUSUM scheme have successfully introduced solar-powered irrigation pumps, laying a foundational groundwork for renewable energy use in rural settings [4]. However, these policies have yet to explicitly incentivize agrivoltaic installations or address the unique needs of soilless systems. Bridging this gap is essential. By expanding policy directives to include agrivoltaics, the government can accelerate the transition to integrated, energy-sustainable farming solutions that uplift farmer incomes and reduce environmental footprints.

A first step involves introducing targeted financial mechanisms. Subsidies on solar infrastructure, soft loans, and feed-in tariffs can offset initial capital costs and make advanced technologies more accessible to smallholder farmers [8]. For instance, guaranteeing a favorable feed-in tariff for solar electricity generated on farms would encourage farmers to invest in PV panels, ensuring a stable revenue stream from surplus energy sales. Similarly, carbon credits and green bonds could link agrivoltaic adoption to climate finance, funneling resources into rural areas where capital is often scarce. Simplifying approval processes through a single-window clearance system would further ease administrative burdens, enabling faster project implementation and scaling [17].

International experiences underscore the importance of regulatory clarity and safeguards to maintain a balance between food and energy production. Taiwan’s over-development of agrivoltaic projects revealed that without clear guidelines, energy generation can overshadow agricultural output [18]. To avoid such imbalances, Japan mandates minimum yield thresholds (80% of standard farming conditions), ensuring that solar infrastructure never compromises core agricultural productivity [9]. France’s definitional approach positions agriculture as the primary activity, with solar energy generation as a secondary, synergistic function [19]. These precedents indicate that India could adopt similar standards—such as maximum shading ratios, minimum panel heights, and yield benchmarks—to preserve agronomic integrity and avoid land-use conflicts.

Moreover, a one-size-fits-all policy will not suffice. India’s diverse agro-climatic conditions demand region-specific guidelines. For example, semi-arid areas might focus on crops suited to partial shading under PV panels, while regions with abundant solar irradiance could prioritize higher panel densities and spectrum-selective technologies. Tailored support would enhance the relevance and uptake of agrivoltaics across states and cropping systems, ensuring optimal outcomes under varying conditions.

Equity and inclusiveness must guide these policy interventions, embodied in the concept of a “Just Transition.” This approach emphasizes that the shift toward low-carbon agriculture—soilless methods powered by agrivoltaics—should yield broad-based benefits rather than reinforce existing inequalities [4]. Smallholder farmers, who often struggle with limited financial resources and technical knowledge, require targeted support: training programs to build capacity in nutrient management and PV maintenance, extension services to facilitate technology adoption, and financial instruments that lower capital barriers. Engaging local research institutions, NGOs, and farmer cooperatives can facilitate bottom-up planning processes, ensuring that agrivoltaic projects align with community priorities and social structures.

Market structures also need refinement. Strengthening supply chains—for both inputs and outputs—enhances the viability of soilless agriculture. Improved storage, cold-chain facilities, and cooperative marketing can amplify the gains achieved from higher yields and year-round production. As farmers adopt these methods integrated with solar PV, their enhanced productivity and reduced input costs should translate into tangible economic gains, particularly if coupled with guaranteed power purchase agreements (PPAs) and stable markets for both produce and electricity [4,8].

Finally, research and development (R&D) investments are critical to drive down costs, improve system reliability, and adapt solutions to local conditions. Collaboration between government agencies, private firms, and academic institutions can foster innovation in PV materials, nutrient formulations, and resource management algorithms. Continuous performance monitoring and data-sharing platforms will ensure lessons learned flow back into policy refinements, maintaining alignment between strategic objectives and on-ground realities.

In sum, well-orchestrated policy and institutional frameworks can convert technical possibilities into widespread practical adoption. By offering clear incentives, streamlined regulations, robust training and finance, and culturally sensitive guidelines, India can ensure that soilless agriculture and agrivoltaics mature into a cornerstone of sustainable rural development. This integrated approach not only addresses energy and resource challenges but also promotes social equity, economic resilience, and agricultural vitality in a world demanding just such solutions.

# 7. Advanced Technologies and the Future of Agrivoltaics and Soilless Systems

As agrivoltaic systems and soilless agriculture gain traction, advanced technologies stand poised to amplify their efficiency, scalability, and resilience. Precision agriculture tools—rooted in Industry 4.0 principles—can optimize resource allocation, fine-tune growing conditions, and maintain system stability even in the face of market fluctuations or environmental variability. Integrating data analytics, machine learning, and the Internet of Things (IoT) with these operations enhances decision-making, reduces labor intensity, and ultimately strengthens farmer confidence.

At the heart of this transformation is real-time monitoring, facilitated by arrays of sensors tracking nutrient composition, pH, humidity, temperature, and CO₂ levels [9,3]. Automated feedback loops adjust nutrient delivery and environmental parameters on the fly, ensuring each plant receives precisely what it needs at each growth stage. By combining these data streams with machine learning algorithms, farmers can predict potential stress factors—such as nutrient imbalances or suboptimal lighting conditions—and intervene proactively. This predictive approach shifts management from reactive to preventive, saving energy and inputs while boosting yields and quality consistency.

Beyond immediate on-farm adjustments, big data analytics and digital twins—virtual replicas of physical systems—enable farmers and policymakers to simulate different scenarios, from altering crop varieties to adjusting panel configurations or testing new lighting schedules [21,22]. Running these simulations in the digital realm allows for rapid experimentation, without risking real-world losses. Over time, these insights accumulate into actionable best practices, facilitating region-specific guidelines that can refine agrivoltaic and soilless approaches for diverse climatic and cultural contexts.

The urban dimension further amplifies the impact of these technologies. Vertical farms, leveraging soilless cultivation under semi-transparent PV panels, can bring sustainable food production closer to consumers [14]. Integrated IoT platforms can streamline logistics, linking production data with downstream supply chains and enabling responsive distribution networks that minimize waste and guarantee freshness. In this manner, advanced technologies bridge the gap between production and consumption, creating closed-loop systems optimized for resource use, greenhouse gas reduction, and consumer trust.

From an energy perspective, IoT-driven control systems can align agrivoltaic power generation with agricultural demands, adjusting lighting and climate control operations to coincide with solar energy peaks [4,8]. By balancing electricity loads against real-time PV outputs, farms can operate more sustainably and reduce reliance on external power sources. Over time, as spectral filters and advanced PV materials improve, agrivoltaic setups may fine-tune the light spectrum reaching crops, enhancing photosynthetic efficiency and further boosting yields with minimal environmental impact [19,20].

Scaling these innovations hinges on robust policy frameworks and active stakeholder engagement. Earlier sections emphasized the need for financial incentives, regulatory clarity, and technical training. Here, advanced technologies reinforce that message: farmers require affordable sensors, user-friendly data dashboards, and reliable connectivity to fully leverage digital agriculture. Cooperative models, capacity-building programs, and public-private partnerships can ensure that smallholders and marginalized communities benefit from these tools. Such inclusiveness is integral to sustaining broad-based support, building trust in new systems, and promoting equitable rural development.

As the sector evolves, continuous R&D efforts will drive improvements in sensor precision, AI-driven decision support, and system interoperability. This relentless innovation opens a path toward dynamic, self-regulating farms that not only conserve resources but also adapt seamlessly to shifting economic and environmental realities. In essence, the integration of advanced technologies and agrivoltaic-soilless systems can reshape agricultural landscapes into intelligent, responsive networks—maximizing productivity and sustainability while reinforcing the resilience of farmers and communities worldwide.

# 8. Comparative Global Insights: Lessons from China and the U.S.

Global case studies offer valuable perspectives on how policy-driven innovation can reshape rural economies and guide the development of integrated agricultural-energy systems. China’s transformation from an agrarian society to a manufacturing and service-driven powerhouse between 1992 and 2012 stands as a striking example of the power of targeted policies and strategic planning [23]. By encouraging rural industrialization—through Township and Village Enterprises (TVEs), the establishment of Special Economic Zones (SEZs), and flexible labor migration mechanisms—China systematically relieved pressure on agriculture, diversified livelihoods, and facilitated the absorption of rural labor into more productive sectors. Although the Chinese experience cannot be transplanted wholesale into the Indian context, the underlying principle is instructive: well-orchestrated policies can catalyze shifts in economic structures, guiding labor and resources toward higher-value activities.

In India, a policy-driven push toward soilless agriculture and agrivoltaics can play a comparable role. Instead of moving labor into manufacturing, India can upgrade its agricultural sector by embracing technologically advanced cultivation methods powered by renewable energy. This redirection can alleviate some of the structural issues plaguing smallholder farmers—limited access to capital, unreliable water supply, erratic market returns—and create stable, long-term growth opportunities. The strategies that China employed to foster skill development and credit availability, or to create enabling environments for entrepreneurship, can inspire Indian policymakers to provide education, training, and financial incentives specifically tailored to these operations. Over time, these interventions can transform agriculture from a low-margin, high-risk endeavor into a more reliable, profitable, and climate-resilient sector.

The U.S. experience with agrivoltaics complements China’s lessons by illustrating the tangible benefits of combining agriculture and renewable energy. American research has highlighted that agrivoltaic systems can create substantial employment opportunities in rural areas, from the construction and maintenance of solar arrays to the management of high-tech cultivation systems [4]. Such job creation is especially crucial in regions where traditional farming might no longer sustain stable employment. By introducing clean energy infrastructure into farming communities, agrivoltaics can stabilize rural economies, encourage local manufacturing of PV components, and stimulate innovation in farm management software, robotics, and nutrient delivery systems.

Moreover, U.S. studies point to the long-term financial viability of agrivoltaics, demonstrating that initial capital investments can be recouped as farmers benefit from higher land-use efficiency and dual revenue streams—cropping and electricity sales [4,8]. These insights underscore the importance of financial instruments and supportive policies mentioned earlier. By aligning energy incentives (like feed-in tariffs or carbon credits) with agricultural productivity goals, governments can create market conditions where adopting soilless agriculture and agrivoltaics becomes not just an environmental imperative, but an economically attractive choice as well.

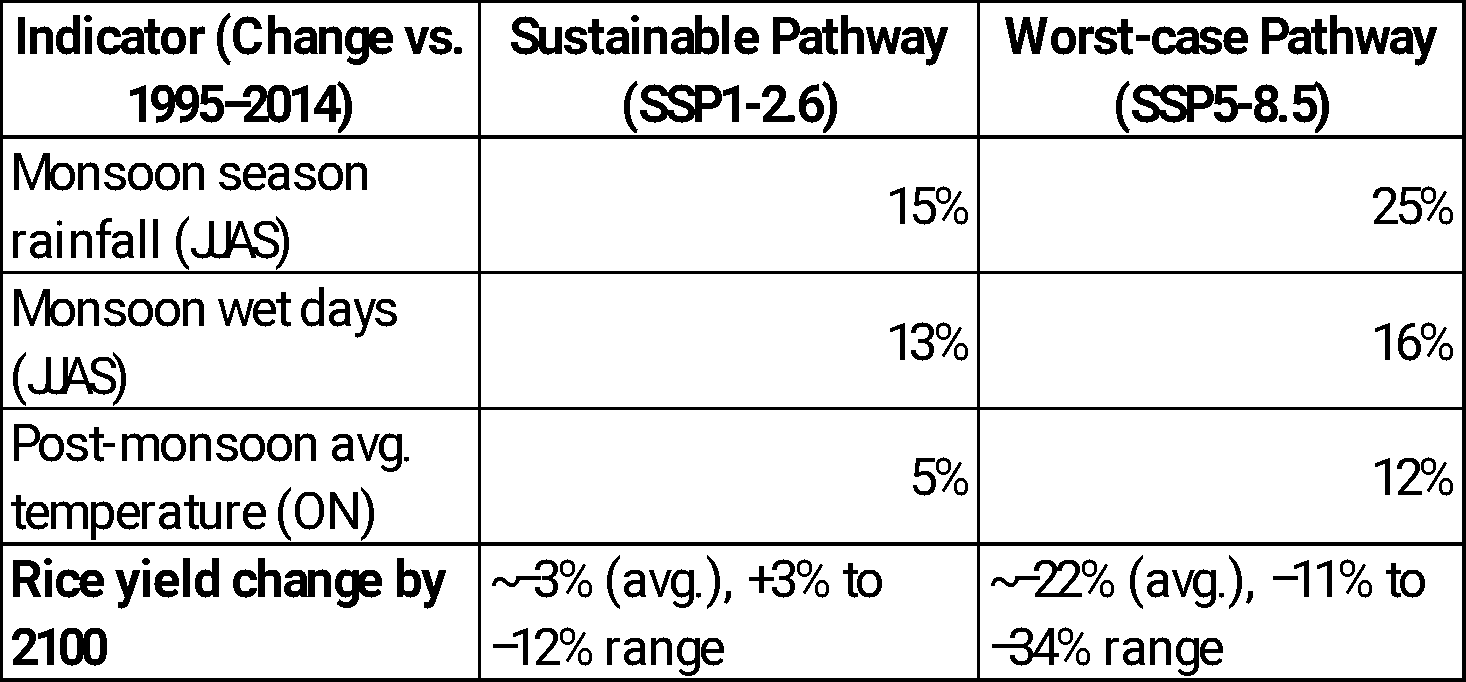
When combined, these global examples highlight a compelling narrative: comprehensive policy frameworks, well-targeted incentives, and strategic education and training initiatives can nudge agricultural economies toward more advanced, resource-efficient models. China’s policy-led transformation shows what can be achieved when governments actively guide labor and resources into new sectors that promise greater returns and resilience. The U.S. examples illustrate how agrivoltaics can deliver on this promise by modernizing agricultural infrastructure and creating rural jobs that align with low-carbon futures.

For India, these lessons reinforce the argument that embracing soilless agriculture and agrivoltaics is not merely a technical upgrade to current farming practices. It is an opportunity to structurally enhance rural livelihoods, diversify income streams, and future-proof the agricultural sector against economic and environmental uncertainties. Such a strategic pivot could position India as a leader in sustainable agricultural innovation, setting a global example of how to combine policy foresight, technology adoption, and integrated land-use planning to meet 21st-century food, energy, and climate challenges.

# 9. Climate Imperatives for Agricultural Transition

Recent climate projections for India underscore an urgent need to rethink conventional open-field farming. The latest CMIP6 model ensembles project increasingly erratic monsoon patterns and rising temperatures across the subcontinent. Monsoon-season (JJAS) rainfall is expected to intensify by about +15% under a low-emissions pathway (SSP1-2.6) and by ~25% in a high-emissions scenario (SSP5-8.5), alongside a rise in the number of rainy days​. Post-monsoon temperatures are projected to climb even more sharply: by the late 21st century, average daily temperatures in the October–November period could increase ~5% in a sustainable scenario versus ~12% under a worst-case scenario​. Such changes imply more frequent extreme rainfall events and prolonged heat stress during critical growing seasons. Crucially, these shifts are poised to depress crop yields. For instance, nationwide rice yields by 2100 are projected to decline by ~3% under SSP1-2.6 and by ~22% under SSP5-8.5 on average, relative to late-20th-century baselines​. In the worst-affected districts, rice productivity could fall by up to one-third under the high-emissions scenario​. Table 1 summarizes these climate projections and their agricultural implications. Taken together, the evidence portrays a future of heightened climate volatility, where heavier downpours, unpredictable rainy seasons, and higher temperatures threaten to disrupt crop development and reduce yields in traditional farming systems. This systemic risk motivates a transition away from monsoon-dependent open-field agriculture. To buffer food production against climate vagaries, India must explore more resilient agricultural models that decouple crop growth from direct weather exposure – notably, controlled environment cultivation and integrated agrivoltaic systems that shield and power crops simultaneously.

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



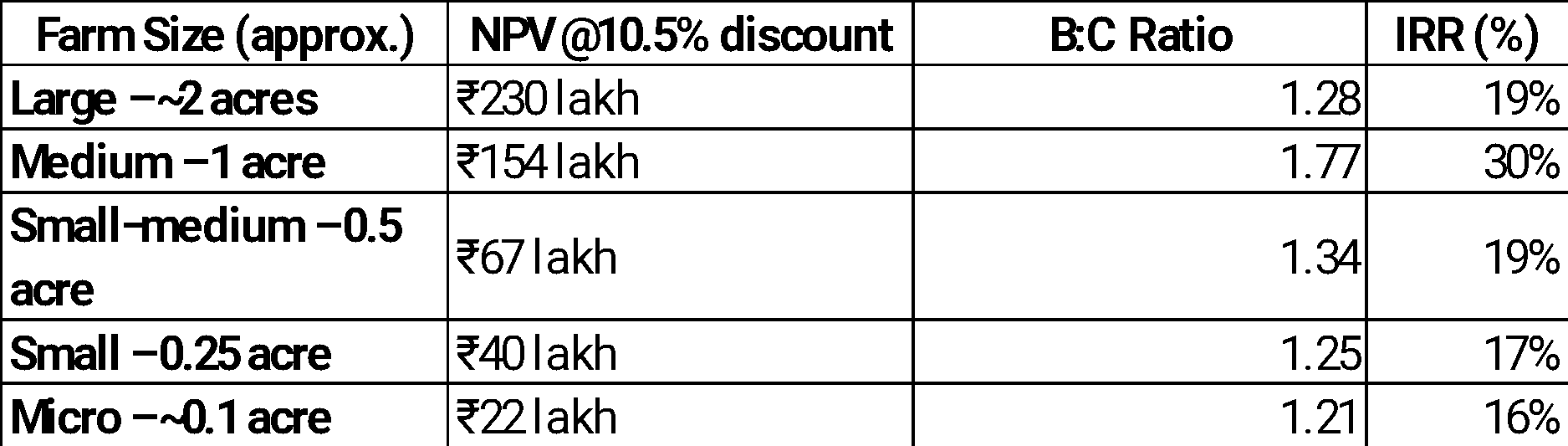
*Note:* JJAS = June–Sept (southwest monsoon); ON = Oct–Nov (post-monsoon). Yield changes are for rice (a monsoon-season staple)​. Positive values indicate an increase; negative (–) indicates a decrease. All districts are projected to experience yield losses under SSP5-8.5​.

These projections highlight that “business-as-usual” farming is increasingly untenable in a warming world. Smallholder farmers, already vulnerable to yearly weather swings, face exacerbated uncertainties as rains become more irregular and temperatures routinely exceed historical norms. In this context, incremental adaptations (like switching crop varieties or tweaking planting dates) may not suffice. The climate imperative is clear: to sustain food security and farmer incomes, agriculture must shift toward systems that can thrive despite climatic volatility. This sets the stage for protected cultivation and soilless farming methods, which offer greater environmental control. By moving production indoors or into regulated environments, and pairing it with renewable energy (e.g. solar-powered agrivoltaics) for cooling and irrigation, farmers can mitigate the direct impacts of extreme weather. The next section examines whether one such innovation—hydroponic farming—is not only climate-resilient but also financially viable in the Indian context.

# 10. Financial Viability of Hydroponic Farming

A critical question for any agricultural transition is economic feasibility: can new methods deliver profitable returns for farmers? Hydroponics, a soilless cultivation technique, has shown promise in resource efficiency and yield, but its adoption hinges on profitability. A recent study by Chaithra *et al.* (2024) analyzed 23 hydroponic farms around Bengaluru to assess their financial performance across different scales. Notably, all surveyed hydroponic enterprises were financially viable, from small setups (~5,000 sq ft) to large installations (~2 acres)​. Key investment indicators are summarized in Table 2. Net present value (NPV) at a 10.5% discount rate was positive for every farm size, ranging from about ₹22 lakh for the smallest units up to ₹230 lakh for the 2-acre farms​. The benefit-cost (B:C) ratios exceeded 1.2 in all cases (i.e., benefits outweighed costs); mid-sized farms (~1 acre) achieved the highest B:C around 1.77, while even the smallest units yielded a respectable B:C of ~1.2. Internal rates of return (IRR) followed a similar pattern – the 1-acre farms attained ~30% IRR, significantly above typical lending rates, whereas the small 5,000 sq ft farms still realized ~16–17% IRR​. These figures decisively refute the notion that hydroponics is only profitable at industrial scales; even modest-scale hydroponic farms can turn a profit in India’s current market.

Table 2. Financial performance of sample hydroponic farms in Bengaluru (Chaithra *et al.* 2024)​



​*Note:* All values are per-farm over a 10-year cash-flow analysis​. NPV: Net present value of net cash flows (rupees lakh, where 1 lakh = 100,000 INR). B:C ratio: benefit-cost ratio (discounted). IRR: internal rate of return. Even the smallest category (5,000 sq ft) had B:C > 1 and IRR well above the 10.5% hurdle rate​. The 1-acre farms exhibited the best overall performance (highest B:C and IRR).

The above results illustrate that hydroponic farming can be economically sustainable across a range of scales. Small and mid-sized operators are able to recover their investments and earn healthy profits, likely due to year-round production of high-value crops (e.g. exotic greens, herbs) and efficient resource use. In fact, the optimal scale appears to be around one acre, which balances the higher output and revenue with manageable costs – as reflected by the peak in B:C ratio and IRR for that category. Larger units (~2 acres) do earn greater absolute profits (highest NPV)​, but they showed slightly lower proportional returns, possibly due to higher initial capital outlays and market constraints on selling a large volume of premium produce. Meanwhile, the viability of even micro-farms is encouraging: it suggests that urban entrepreneurs or smallholder farmers with limited land can still adopt hydroponics as a profitable enterprise, supplementing their income or diversifying away from climate-sensitive field crops.

To translate this economic potential into widespread adoption, supportive policy mechanisms will be vital. High setup costs remain a barrier for many prospective growers (e.g. specialized structures, pumps, and control systems require upfront investment)​. Governments and financial institutions can help de-risk these investments through low-interest loans, capital subsidies, or tax incentives for hydroponic projects. Additionally, training and extension services are needed to build technical capacity in managing nutrient solutions and controlled environments, ensuring that even those new to soilless cultivation can achieve the performance levels reported in Bengaluru. Strengthening market linkages is equally important: as more producers enter the space, supply chains for inputs (nutrients, seedlings) and outputs (fresh produce marketing) must be developed to maintain profitability and quality standards. By implementing such support measures, policymakers can empower farmers to transition to hydroponics—an innovation that aligns with India’s climate adaptation needs and offers a financially viable path forward. This synergy between climate resilience and economic return makes a compelling case for integrating soilless agriculture (and complementary agrivoltaic energy supply) into the country’s agricultural roadmap.

# 11. Conclusion

Global population pressures, climate-induced resource scarcities, and India’s specific agrarian constraints demand a radical departure from traditional agricultural models. Soilless agriculture, when complemented by renewable energy, not only maximizes resource efficiency but also stabilizes production against environmental and market uncertainties. By embracing agrivoltaics—co-locating solar arrays with cultivation systems—producers can integrate food and energy generation, reducing environmental footprints, cutting reliance on external inputs, and diversifying farm incomes.

Realizing this potential, however, requires more than technical adjustments. Strategic policies—subsidies, feed-in tariffs, single-window clearances, and region-specific standards—must incentivize adoption while ensuring equitable access for smallholders and marginalized communities. Drawing on international insights, India can employ a “Just Transition” framework to align these innovations with rural employment, infrastructure development, and long-term financial viability. In doing so, the nation can transform its agricultural sector into a resilient, inclusive, and sustainable engine of growth—securing food supplies, uplifting rural economies, and setting a global standard for integrating soilless agriculture and renewable energy.

# 12. References

(1) United Nations. (2017). *World Population Prospects.*  
(2) The India Forum. (2021). *India’s Biggest Challenge: The Future of Farming.* Retrieved from <https://www.theindiaforum.in/article/india-s-biggest-challenge-future-farming>  
(3) Resh, H. M. (2013). *Hydroponic Food Production* (7th ed.). CRC Press.  
(4) Worringham, C. (2021). *Agrivoltaics in India: Fertile Ground?* Institute for Energy Economics and Financial Analysis (IEEFA).  
(5) Barbosa, G. L., et al. (2015). Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods. *International Journal of Environmental Research and Public Health*, 12(6), 6879-6891.  
(6) Dupraz, C., Marrou, H., Talbot, G., Dufour, L., Nogier, A., & Ferard, Y. (2011). Combining Solar Photovoltaic Panels and Food Crops for Optimizing Land Use: Towards New Agrivoltaic Schemes. *Renewable Energy*, 36(10), 2725–2732.  
(7) FAO. (2017). *The Future of Food and Agriculture – Trends and Challenges.*  
(8) Amaducci, S., Yin, X., & Colauzzi, M. (2018). Agrivoltaic systems to optimize land use for electric energy production. *Applied Energy*, 220, 545–561.  
(9) Barron-Gafford, G. A., et al. (2019). Agrivoltaics Provide Mutual Benefits Across the Food–Energy–Water Nexus in Drylands. *Nature Sustainability*, 2(9), 848–855.  
(10) FAO. (2016). *AQUASTAT Main Database.* Food and Agriculture Organization of the United Nations.  
(11) IJFMR. (2021). Hydroponics: A Review. *International Journal For Multidisciplinary Research*, 3(4), 10-15.  
(12) Agrivoltaics-in-India\_December-2021 (IEEFA’s report) [Same as Worringham (2021), already listed as (4)]  
(13) MNREGA Act and related policy discussions as mentioned in The India Forum article.  
(14) Despommier, D. (2010). *The Vertical Farm: Feeding the World in the 21st Century.* Thomas Dunne Books.  
(15) Elamri, Y., Cheviron, B., Lopez, J. M., Dejean, C., & Belaud, G. (2018). Water Budget and Crop Modelling for Agrivoltaic Systems: Application to Irrigated Lettuce. *Agricultural Water Management*, 208, 440–453.  
(16) Agrawal, S., Tiwari, A. N., & Tiwari, G. N. (2017). Performance Analysis of Semi-transparent Photovoltaic Module Integrated Solar Greenhouse for Different Vegetables in Different Climatic Conditions. *Solar Energy*, 155, 1133–1145.  
(17) IRENA. (2019). *Renewable Energy Policies in a Time of Transition.*  
(18) ADEME. (n.d.). *Agrivoltaics Best Practices Report.*  
(19) Roccaforte, G. (2021). Eclipse: A New Photovoltaic Panel Designed for Greenhouses and Croplands. *AIP Conference Proceedings*, 2361(1), 070002.  
(20) Wang, Y., Yu, Q., Zhang, L., Xu, W., Liu, M., & Ye, Y. (2021). Design of Spectrally Selective Agrivoltaic Systems with Organic Solar Cells. *Advanced Energy Materials*, 11(2), 2002882.  
(21) Dinesh, D., et al. (2018). Digital Agriculture for Small-Scale Farmers. *CGIAR Platform for Big Data in Agriculture.*  
(22) Mazzetto, F., Calcante, A., & Mazzetto, T. (2017). Precision Agriculture and Knowledge Management 4.0. *Agricultural Informatics Journal*, 8(2), 57–65.  
(23) China Industrialisation reference from the user’s draft (Exact source not provided, cited as "China Industrialisation, Source 13").