



## Solar Technology in Agriculture

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### Abstract

Solar technology is revolutionizing agriculture by providing clean, renewable energy for irrigation, farm machinery, cold storage and daily operations. Shifting from fossil fuels to solar-powered solutions helps farmers reduce operational costs, improve efficiency and lower carbon emissions worldwide. Key innovations such as solar-powered irrigation pumps, greenhouse heating systems, pest management tools and off-grid energy supplies increase agricultural productivity and support resilience, especially in areas with unreliable electricity access. Solar irrigation, exemplified by India's PM-KUSUM scheme, offers substantial energy savings and income opportunities by enabling farmers to sell surplus power. Solar greenhouses extend growing seasons and reduce energy costs by utilizing both active and passive solar heating. Solar pest management reduces reliance on chemical pesticides. Off-grid solar mini-grids empower remote farms, promoting rural electrification and productivity. Additional applications include solar-powered livestock water pumps, monitoring systems, agrivoltaics combining crop cultivation and power generation and solar refrigerators combating post-harvest losses. Government incentives and financing models, such as those in India and the US, have been pivotal in making solar technology accessible to small and marginal farmers. Collectively, these solar innovations not only advance sustainable farming by reducing greenhouse gas emissions but also strengthen rural economies and food security. The future of agriculture increasingly depends on harnessing solar energy to foster resilience, environmental stewardship and economic viability.

**Keywords:** Solar, Irrigation, Storage, Off-grid, Fuel, Greenhouse

### Introduction

Modern agriculture stands at a crossroads, challenged by the dual pressures of escalating energy costs and an urgent imperative to adopt more sustainable practices. Traditional agricultural systems have long relied on fossil fuels for essential processes such as irrigation, mechanized farming, processing and the transportation of goods. This dependence not only places a significant financial burden on farmers, given the volatility and rising prices of petroleum-based inputs, but also exacerbates environmental concerns by contributing heavily to greenhouse gas emissions. According to the Food and Agriculture Organization (FAO), agriculture accounts for nearly 30% of global greenhouse gas emissions when considering the full food system, with a large portion attributable to energy use in farming operations.

Amidst these challenges, solar technology has emerged as a transformative force enabling agriculture to decouple itself from conventional, polluting energy sources. The key to this transformation lies in the harnessing of solar energy through photovoltaic (PV) panels, which convert sunlight a free and abundant resource into electricity. This electricity can power a broad spectrum of agricultural activities, ranging from irrigation pumps and farm machinery to greenhouse climate systems, cold storage units, pest control devices and even rural electrification projects. The decentralization and reliability of solar energy not only enhance energy access for remote and off-grid farms but also empower smallholders and marginal farmers, who are often most vulnerable to fluctuations in energy costs and climate change impacts.

Received: 21 August 2025  
Revised: 28 August 2025  
Accepted: 29 August 2025  
Published online: 2 September 2025

Article ID: SR01022

Citation: Nath, C. & Barman, B. (2025). Solar Technology in Agriculture. *Scientia Review*, 1(3), 25-29

A striking factor propelling the widespread adoption of solar technology in agriculture has been the dramatic decline in the cost of solar PV modules. Data from the International Renewable Energy Agency (IRENA) shows that between 2010 and 2024, the average global price of solar panels fell by nearly 80%. This cost reduction has made solar installations increasingly affordable, allowing both small-scale family farms and large commercial enterprises to invest in renewable power. The economic case for solar is further strengthened by its low maintenance requirements, exemption from fuel supply disruptions and eligibility for various government incentives and subsidies aimed at promoting clean energy. For example, India's Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM) scheme and the United States Department of Agriculture's Rural Energy for America Program (REAP) have played instrumental roles in scaling up agricultural solar adoption (MNRE India, 2023; USDA REAP, 2024).

Solar energy's integration into agriculture is also closely intertwined with the evolution of precision agriculture. Advances in monitoring and automation, now increasingly powered by solar energy, enable data-driven decision-making to optimize water usage, fertilizer application and crop protection. This synergy between solar power and smart farming technologies is helping farmers maximize yields, reduce waste and improve resilience to weather variability.

This examines the multi-dimensional impact of solar energy on the agricultural sector as of 2025. It will explore current trends; practical case studies and the outcomes realized through field deployment of solar-powered systems. Additionally, it considers how policy frameworks, financing models and technological innovations have catalyzed the solar revolution in farming communities across the globe. Ultimately, the adoption of solar technology represents not merely a shift in how farms are powered, but a fundamental

transformation toward a more resilient, efficient and sustainable agriculture for the future.

### Solar-Powered Irrigation Systems

Solar-powered irrigation sits at the heart of modern solar agriculture, promising reliable water access while eliminating dependency on costly fossil fuels. With photovoltaic (PV) panels capturing sunlight and converting it into electricity, farmers can power submersible and surface irrigation pumps even in the most remote or off-grid locations. This technology has proven transformative, particularly across India, where erratic rainfall and insufficient grid access often threaten crop security. A prime example is the government-driven PM-KUSUM scheme, launched in 2019. The scheme set out to install 1.75 million standalone solar pumps and solarize an additional 1 million grid-connected agricultural pumps by March 2026. As of May 2024, over 352,000 solar pumps had been installed under this program, benefiting both crop and livestock farmers (**Table 1**) (MNRE India, 2024).

The financial benefits of solar irrigation are substantial. After the initial investment, much of which is subsidized, farmers report up to 60% reductions in their energy costs compared to diesel-based systems. This technology not only removes the unpredictability of diesel prices and availability but also generates clean, quiet energy, reducing greenhouse gas emissions significantly. Moreover, many farmers who install grid-connected solar pumps are able to sell surplus electricity back to the local power grid, creating a supplementary source of income that further bolsters rural economies. Rajasthan stands out as a notable success story, with more than 50,000 solar irrigation pumps supporting agriculture and animal husbandry in arid regions. These solar installations assure consistent water supply, helping farmers manage their fields more efficiently and expanding their cropping choices even during dry seasons (Morca Pumps, 2023; Rajasthan Govt, 2024).

**Table 1:** Solar irrigation pump installations and their impacts in India

Country/Region	Solar Pumps Installed	Key Outcome
India (as of May 2024)	352,138	Up to 60% energy cost reduction
Rajasthan	50,000+	Reliable irrigation for arid farms
PM-KUSUM (Target by 2026)	1.75 million	Major diesel reduction, extra farmer income

### Solar Energy for Greenhouse Heating

The integration of solar power in greenhouses represents a leap in sustainable, controlled-environment farming. Traditional greenhouses require significant energy input to maintain optimal growing conditions, especially for off-season or high-value crops. Solar PV panels offer a sustainable and cost-effective way to heat greenhouses during the cold months and power essential systems such as lighting, irrigation and climate control mechanisms. In addition to active generation, greenhouses can apply passive solar principles utilizing the sun's warmth for thermal mass storage and retention (LREDA, 2023).

Studies show that with solar-powered greenhouses, operational costs drop considerably, usually recovering initial investments within five to ten years. After this payback period, the continued energy savings directly enhance farm profitability. The environmental advantages are clear: switching to renewable solar power cuts carbon emissions and decouples food production from fossil fuel volatility. This is especially crucial in colder regions or places with weak grid connectivity, such as Ladakh in India, where solar-powered greenhouses have extended vegetable crop seasons by up to three months, increasing both local food security and farmer incomes (Renewable Energy Journal, 2022; MNRE India, 2023).

### Solar-Powered Pest Management

Farmers across India and globally are turning to solar-powered pest management as a sustainable alternative to chemical pesticide use. Solar insect traps and electronic deterrents fueled by solar PV panels deploy ultraviolet or specialized lights to attract, trap or repel problematic insects from fields of cotton, maize and vegetables. In Maharashtra and Kenya, the introduction of these devices has led to a documented reduction of chemical pesticide application by 30-40%. This not only improves the environmental impact by lowering the chemical load on soil and water but also results in healthier crops and lower input costs (Agri-route, 2023; IJCMS, 2021).

An interesting example can be seen in Vidarbha, India, where UV-filter-based solar traps have attracted up to 57% of phototrophic (light-seeking) pest species, integrating seamlessly with broader pest management strategies. Such adoption demonstrates the vital role solar can play in integrated pest management systems that protect both crop yields and farmer health.

### Solar Water Pumps for Livestock

Reliable access to water is a persistent challenge for livestock farmers, especially in arid or semi-arid areas. Solar-powered water pumps address this need by utilizing PV-driven systems to extract groundwater for animal troughs, supporting animal health and productivity. This technology is gaining ground in regions like Rajasthan, India and rural Australia, where reaching remote wells with grid electricity or transporting fuel is economically prohibitive.

Adopting solar-powered pumps eliminates the need for diesel generators, thereby reducing operational costs and the environmental footprint of livestock operations. As water security improves, so too do livestock health and productivity, helping secure rural livelihoods and promoting more resilient agricultural practices.

### Off-grid Solar Systems for Remote Farms

Many farms around the world operate outside the reach of central electricity grids, limiting their ability to upgrade or expand operations. Solar mini-grids and distributed off-grid PV systems enable these remote locations to become self-reliant. In Jharkhand, India, over 100,000 farmers now benefit from solar-powered infrastructure. Such systems provide essential energy for irrigation, storage, processing and household needs.

These installations range from modest rooftop panels to mini-grids with capacities of 20–40 kW, often supporting clusters of farms and small rural enterprises, especially those managed by women. By delivering stable, affordable power where it was previously unavailable, off-grid solar systems are lifting rural productivity and incomes while reducing the dependence on polluting diesel generators (Mongabay, 2023; MNRE India, 2024).

### Solar-Powered Monitoring, Surveillance and Lighting

Smart agriculture increasingly relies on sensor-based monitoring and automation, powered reliably by solar energy. In Punjab, India, solar-powered moisture and weather sensors guide irrigation schedules for wheat and rice, resulting in water savings of 20–30%. These innovations help optimize resource usage and improve agricultural efficiency.

Likewise, security cameras and farm lighting systems powered by solar panels are transforming farm management. In Madhya Pradesh, for example, more than 200,000 solar-powered LED lights now illuminate farmyards, storage spaces and roads, making these areas safer and extending productive hours well into the evening, all while incurring minimal

electricity costs (PM-KUSUM Punjab, 2024; The Better India, 2023).

### **Agrivoltaics (Combining Solar Panels and Crops)**

Agrivoltaics marks a significant innovation in land-use efficiency. By installing solar PV panels high above cropland, farmers can simultaneously produce food and renewable energy from the same land parcel. In Tamil Nadu, India, agrivoltaic projects have reported up to 60% increases in land-use efficiency, as energy infrastructure and agriculture coexist.

Other regions, such as Germany, have adopted this approach as well, using elevated panels that provide partial shade. This can reduce soil moisture evaporation, protect crops from extreme heat and support year-round production. Agrivoltaics thus offers resilient solutions in the face of both climate change and agricultural land pressures.

### **Solar-Heated Barns and Livestock Shelters**

Solar energy is also being harnessed to maintain comfortable environments for livestock, particularly during cold seasons. Solar thermal systems and PV-powered heaters stabilize barn temperatures, reducing animal stress and boosting yields. In Himachal Pradesh, India, dairy farms have achieved 15–20% reductions in heating expenses while seeing improvements in milk production thanks to more stable, animal-friendly environments.

These systems lower fossil fuel dependence and serve as a template for eco-friendly livestock management, particularly valuable in regions with high seasonal temperature swings.

### **Portable Solar Generators**

For farms with dispersed plots or those requiring mobility, portable solar generators offer a flexible, clean energy solution. In Gujarat, India and many parts of Europe, these compact units power critical field equipment pumps, lights and processing tools reducing fuel costs by 25–30%. Their portability means equipment can be used wherever it's needed, making day-to-day farm operations more efficient and less reliant on costly diesel or gasoline generators (Morca Pumps, 2023; European Solar Association, 2024).

### **Solar Refrigeration for Post-Harvest Storage**

One of the most critical post-harvest challenges, particularly for smallholder farmers, is the preservation of perishable crops. Solar-powered refrigeration using PV energy to run cold storage units offers an environmentally sustainable way to reduce spoilage. In Karnataka, India, solar cold rooms have been instrumental in reducing

post-harvest losses by as much as 40%, particularly for fruits and vegetables. By enabling extended and more secure storage, farmers can secure better market prices and reduce the risk of crop waste (MNRE India, 2024; Food Loss and Waste Protocol, 2023).

### **Solar in Aquaculture**

Beyond traditional crop and livestock farming, solar power is making significant inroads in aquaculture. In innovative systems called "aquavoltaics," regions like Kerala, India and Croatia are integrating PV panels with fish farms. The solar installations power aerators, water circulators and temperature control equipment, ensuring optimal aquatic conditions and improving yields. Kerala's experience shows a 30% improvement in fish farm efficiency, with significant savings in operational costs and lower reliance on grid power or diesel fuel (Kerala Fisheries Dept., 2023; IRENA, 2023).

### **Financing and Government Incentives**

The widespread adoption of solar technology in agriculture has been made possible largely due to supportive government policies and generous financing structures. In India, central and state schemes including the PM-KUSUM program subsidize up to 70% of the costs associated with solar pumps and agrivoltaic systems, making clean energy accessible to even small and marginal farmers.

In the United States, the Rural Energy for America Program (REAP) offers comparable incentives, underwriting up to 70% of the total installation expenses for solar energy projects on farms and rural businesses. Such financial models are critical to scaling up the technology's deployment and delivering widespread benefits (MNRE India, 2023; USDA REAP, 2024).

### **Photovoltaic Panels for General Farm Operations**

Beyond specialty uses, solar PV is increasingly becoming the backbone of everyday farm operations. Farms and agro-processing centers use solar electricity to power machinery, equipment and even entire communities. Maharashtra, India and several regions in France have adopted large-scale farm-based solar plants, collectively generating over 500 MW annually. This locally produced energy supports on-farm operations, processing units and rural electrification, promoting both sustainability and rural economic growth (MNRE India, 2023; USDA REAP, 2024).

### **Solar Dehydrators**

Solar-powered dehydrators are transforming food preservation. Unlike traditional fuel-fired

dryers, solar dehydrators harness the sun's energy to gradually extract moisture from fruits, vegetables and herbs, effectively extending shelf life. In Andhra Pradesh, India, these devices have shown an ability to increase crop shelf life by up to 50%, reducing spoilage and enabling farmers to market their produce for longer periods and during off-seasons (Andhra Pradesh Renewable Energy Centre, 2023; FAO, 2022).

### Conclusion

One of the most transformative aspects is the way solar energy democratizes access to power, particularly in remote and off-grid areas historically left behind in rural development. Small and marginal farmers often the most vulnerable to cost fluctuations and resource scarcity are finding new economic security through subsidized solar pumps, the creation of supplementary income streams by selling excess power and dramatically lowered fuel expenses. With innovative applications such as agrivoltaics, farms no longer face a trade-off between energy production and food cultivation, as the two can now thrive in tandem on the same parcel of land, improving overall land use efficiency and bolstering food-energy security.

Subsidies, government programs and robust private sector involvement have made the initial investments in solar infrastructure more accessible, ensuring that the cost barrier does not impede the transition toward greener agriculture. Major national efforts such as India's PM-KUSUM scheme and the United States' REAP initiative have set global benchmarks for policy-driven adoption, demonstrating how state support can be pivotal in scaling clean energy technologies and encouraging sustainable development.

Equally important are the environmental outcomes: reductions in carbon emissions, minimized reliance on chemical pesticides through solar-powered pest management and lower consumption of fossil fuels across farm operations. These environmental benefits do not come at the expense of profitability but instead reinforce it, through lower operational costs, improved crop quality, enhanced livestock productivity and preserved post-harvest value.

The solar revolution in agriculture is already shining across continents from India and Kenya to France, Germany, Australia and the United States. Its success stories from extending vegetable growing seasons in Ladakh to improving aquaculture efficiency in Kerala highlight the adaptability and universality of solar technology.

In sum, solar technology is empowering a new agricultural paradigm one where energy is secure and sustainable, yields are robust, rural economies grow stronger and the sector is equipped to face the uncertainties of a changing climate. The continued evolution and adoption of solar agricultural solutions will be essential to meeting the world's growing food demands while preserving the environment for future generations. Solar energy's role in agriculture has shifted from an innovative experiment to a vital path forward for global food security and sustainable rural livelihoods.

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