A COMPREHENSIVE REVIEW OF SOLAR POWER USAGE IN AGRICULTURE: A WAY FORWARD TO ACHIEVE SUSTAINABLE DEVELOPMENT GOALS (SDGS)

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Abstract

Agriculture is witnessing a shift toward renewable energy, as it reduces the dependence on fossil fuels and eliminates greenhouse gas emissions (Turkmen, 2020). In India, access to nonrenewable energy for the agricultural production process is beyond reach in remote places. Globally, solar energy plays a vital role and is mechanically integrated into agriculture as a cost-effective alternative to traditional energy sources. Its applications range from solar-powered irrigation to processing and further enhancing crop yields globally. The study examines a range of past studies from 2020 onward, as well as relevant research on the application of solar-powered technologies in agriculture, contributing to sustainability. The study will utilize secondary data retrieved from Elsevier Scopus, ScienceDirect, EBSCO, working papers, industry reports, and reports of government bodies. The data collected will be statistical figures on renewable energy use by the farming community, and research papers on agricultural sustainability, renewable energy use by farmers, and the applications of solar-powered technologies in agriculture will be collected and analyzed. Future researchers can focus on climate-smart renewable energy solutions tailored to agricultural practices. The present study recommends that researchers evaluate cost–benefit analysis, socioeconomic impacts on farmers, and marginalized groups. Policymakers can deliver handholding support for adoption through targeted subsidies, low-interest financing, and incentives for solar-powered technologies.

Keywords: Sustainability, agriculture, farmers, solar, and SDGs

Introduction

Earth is a product of change, and agriculture is no different. In the erstwhile, the cultivation of wild crop varieties started approximately 10000 BC, and present-day agriculture has always changed. The changes that are efficient and beneficial swallow inefficient and detrimental changes. Thus, various advancements have been achieved throughout human history. At present, the efficiency metric has led us to mechanical system-dependent agriculture, including biological system-dependent agriculture. A mechanical machine, by nature, can consistently outwork a human with greater precision in activity. However, most mechanical machines work on energy, either directly delivered (AC) or indirectly (diesel motors). Therefore, the energy requirement is a common goal, so the question arises as to which method produces the most efficient power. However, diesel is cheap, reliable, and abundant, has detrimental effects on the environment and is inefficient in its conversion. Therefore, electricity is preferred for various power-consuming units, such as houses and production units. The energy requirement only increases as time progresses, as the efficiency of machines is greater than that of human labor, and the same is true for agriculture. Here, as the energy requirement increases, the exploitation of fossil fuels increases, which in turn can have dangerous impacts on the environment; thus, the SDGs are set to restrict single-minded exploitation in the case of efficiency and redirect it to the growth of more sustainable fields. Instead of fossil fuel energy, energy is obtained through renewable energy methods such as photovoltaics, and research is promoted in fields that promote sustainability.Innovations in sustainability are promoted more openly and with exigency, which can be viewed through the SDGs of zero hunger, clean energy, and responsible production (Y Cai et al., 2021). The sustainable goals objective pushes for a reduction in fossil fuel usage, which then leads to a search for an alternative. This is where we arrive at solar energy tapping, as recent studies have shown that an alternative to fossil fuel in farming is solar energy (Panda SN et al., 2024). Solar energy is the leading alternative, as it has a better dependency rate and provides easy access in rural areas, as it does not require a grid connection, which in turn assists farmers in ensuring food security and ensures income to the farmers (Journal I, 2024). However, only considering these factors ignores a major factor called socioeconomic and political factors concerning the adoption of solar power (Roy P et al., 2025).

Sustainable goals also involve human aspects, so ensuring that everyone has a fair chance is crucial (Harris et al., 2024). The studies have focused mostly on large farmers with larger production units and capacity, which disregards crucial factors of adaptation for small and marginal farmers who are essential for global food supplies and who are suffering the most from climatic swings (Panda SN et al., 2024). Although solar power is promoted and said to have a great future ahead, some questions such as how it is maintained in a local setting, whether the local ecosystem can support it and the short- and long-term goals and economic benefits of these systems to farmers remain (E M B M Karunathilake et al., 2023). From an administrative point of view, questions such as what kind of government backing is needed and what policies should be adopted are necessary (Magarelli A et al., 2024).

The objective of this review is to document the evidence on the growth of segment wise solar market, rationale behind growing demand for solar powered technology in agriculture and to review the impact of solar-powered technologies in agriculture and their contribution to sustainable agricultural practices in alignment with the following goals: SDG 7- Affordable and Clean Energy; SDG 12-Responsible Consumption and Production; and SDG 13- Climate Action.

Methodology

The study is a secondary data survey. Firstly, relevant information to support the rationale and growth of various segments of the solar market was analysed by collecting data from multiple sources. Second, past studies from 2020 onward were sorted to identify research on the application of solar-powered technologies in agriculture and their contribution to sustainability. Secondary data was obtained from Elsevier Scopus, Web of Science, ScienceDirect, working papers, industry reports, and government reports. The data collected includes statistical figures on renewable energy use by the farming community and research papers on agricultural sustainability, renewable energy use by farmers, and applications of solar-powered technologies in agriculture. Articles were selected by filtering the publication time from 2020-2025 and searching with keywords such as "solar energy impacts on farming" and "sustainability." The articles were reviewed to identify research gaps for further study. Relevant articles from various journal databases are listed in Table 1.

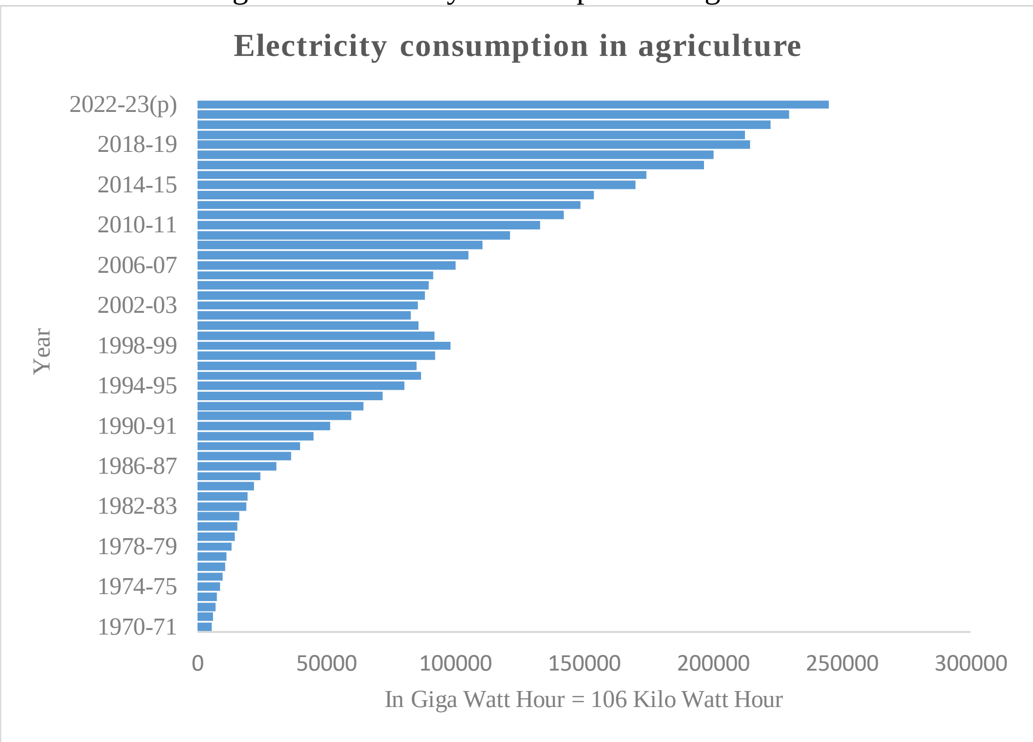
Table 1. Selection of relevant articles from journal databases (from 2020--2025)

S.no.	Journal database	Number of relevant articles
1.	Scopus	6
2.	Academia	6
3.	Web of Science	9
4.	ScienceDirect	11
	Total	32

A scenario of electricity consumption in Indian agriculture

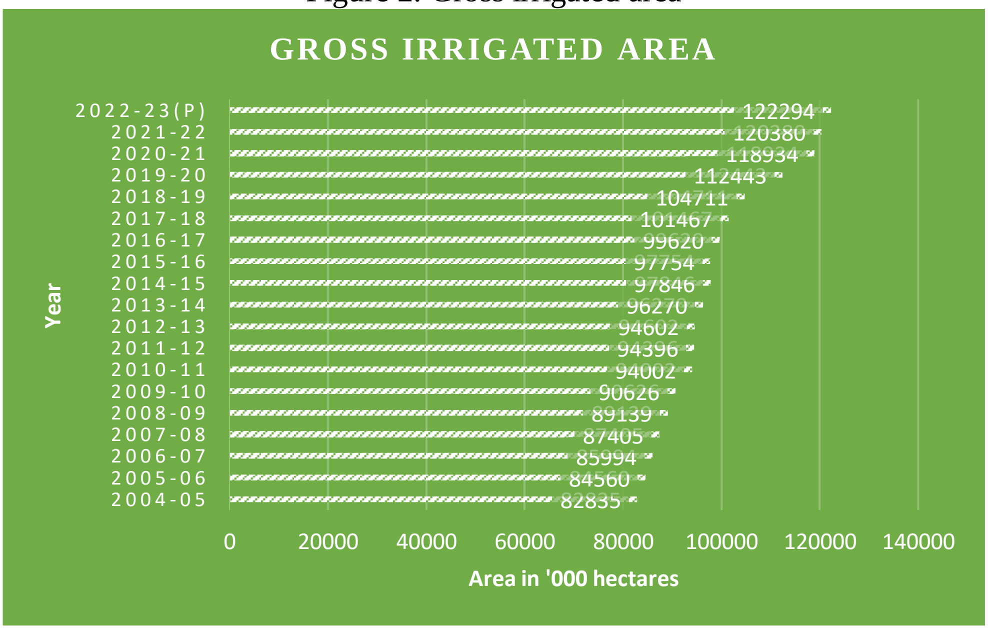
One of the indispensable inputs to farming is electricity, as it is crucial for pumping water for irrigation from the groundwater table.

Figure 1. Electricity Consumption in Agriculture



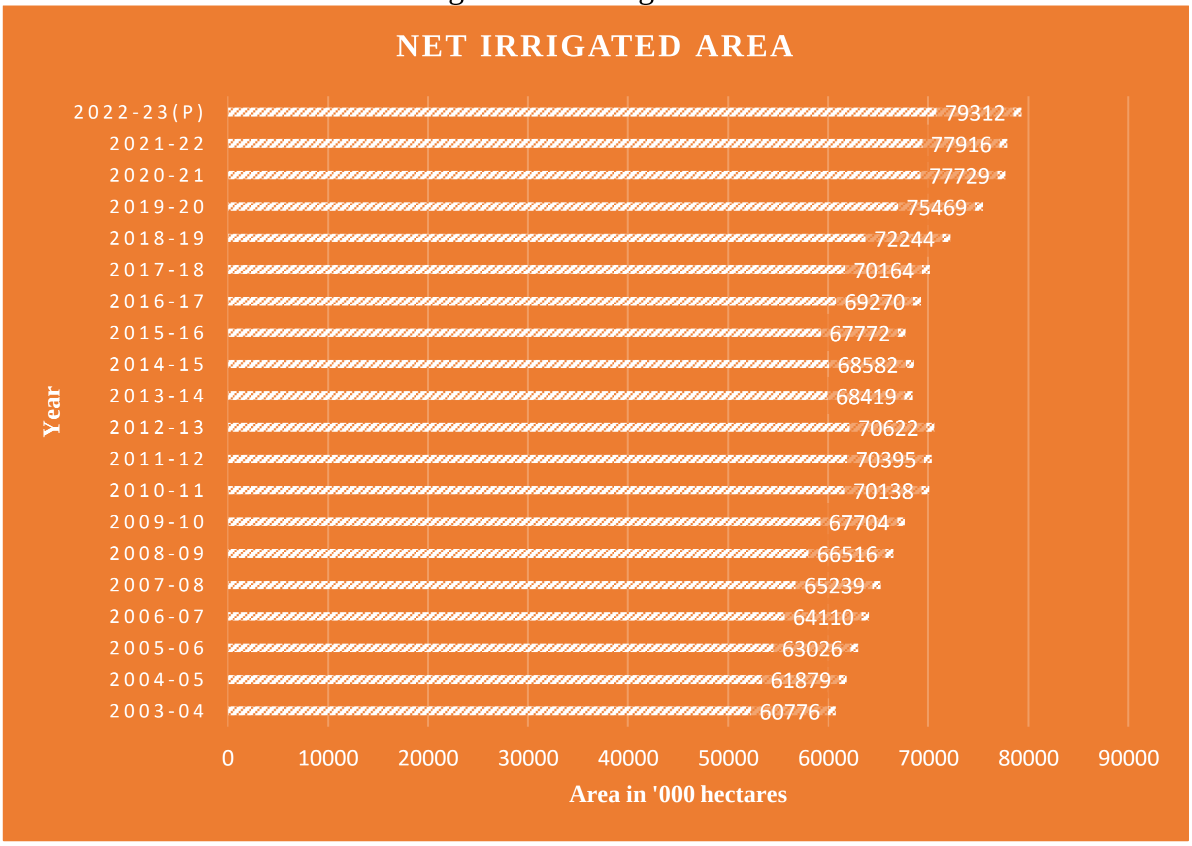
(Source: Indiastat data on power consumption in agriculture, graph generated by author)

Figure 2. Gross irrigated area



(Source: Land Use Statistics at a Glance: 2022-23, graph generated by author)

Figure 3. Net irrigated area



(Source: Land Use Statistics at a Glance: 2022-23, graph generated by author)

Figure 1, illustrates that electricity consumption has increased over the years, highlighting the growing demand for electricity in crop production. At the same time, fig 2 & 3 showing the gross and net irrigated areas used for agriculture, have steadily expanded. Between 2003-04 and 2022-23, electricity demand in agriculture grew at a compound rate of 6.00%, while gross and net irrigated areas grew at 2.04% and 1.19% respectively.

Status of the solar market segment in agriculture

In agriculture, the solar-based products and their markets are segmented into solar-based water pumps, dryers, greenhouses, electric fencing, and lawn mowers. These markets are at a nascent stage of development in India. Due to its development phase, there is no proper documentation and reports available for studies and market research. An attempt has been made to collect the secondary data on the current year to make a growth comparison to the previous year at the global level and in India in 2023 and 2024. Table 1 on segment-wise growth of the solar market is given below.

Table 1. Segment-wise growth of the solar market

Segment	**2023 Global Market Size (USD Billion)**	**2024 Global Market Size (USD Billion)**	**Global Growth (%)**	**2023 Market Size India (USD Billion)**	**2024 Market Size India (USD Billion)**	**India growth**	**Sources (attached in data references)**
Solar Pump	2.63	2.77	5.32	0.45	0.52	**15.56**	Grand View Research [1] Precedence Research [11] Markets and data [12]

Segment	2023 Global Market Size (USD Billion)	2024 Global Market Size (USD Billion)	Global Growth (%)	2023 Market Size India (USD Billion)	2024 Market Size India (USD Billion)	India growth	Sources (attached in data references)
							Research and markets [13]
Solar Sprayer	0.57	0.81	42.11	Nil	Nil	Nil	WiseGuyReports[23]
Solar Greenhouse	2.5	3.0	20.00	Nil	Nil	Nil	MarketReportAnalytics[4]
Solar Electric Fencing	0.33	0.35	6.06	Nil	Nil	Nil	Fortune Business Insights [5]
Solar Lawn Mowers	1.2	1.25	4.17	Nil	Nil	Nil	VerifiedMarketReports[67]
Solar Dryer	0.7	0.81	15.71	Nil	Nil	Nil	DataIntelo/industry media (for India) [10]

Table 1 shows that, at the global level, solar-powered sprayers experienced the highest growth at 42.11 percent, followed by 20 percent growth in solar greenhouses, and 15.71 percent in solar dryers, fencing, pumps, and mowers. In contrast, in India, solar pumps recorded a compound growth rate of 15.56 percent, while market data for other products is unavailable.

Review of past studies on solar-powered technologies in agriculture

The application of solar power in agriculture has advanced significantly. The utilization of solar energy could reduce environmental stressors and increase crop yields (Y Cai et al., 2021; Panda SN et al., 2024). For a sustainable future, traditional farming methods have been combined with concepts from renewable energy. People began connecting solar energy to more general objectives such as food security and climate resilience as interest grew over time (Bryan E. Escoto et al., 2024), (Journal I, 2024). Developments in renewable energy drove the industry toward greenhouses and solar irrigation, reducing the need for fossil fuels and promoting crop growth once more (Roy P et al., 2025), (M S Sujatha et al., 2024). In addition to their positive effects on the environment, they also improved rural livelihoods by offering new local job opportunities, thus lending a hand to policy makers ((Harris I et al., 2024), (Panda SN et al., 2024)). These advancements have helped scholars focus on issues related to finance and the gap in information in technology, further pushing them to take a holistic approach to technology, policy and community. These developments, tracked carefully over the years, paint a picture of solar energy as a real contributor to a more sustainable farming future ((E M B M Karunathilake et al., 2023), (Magarelli A et al., 2024), (Time A et al., 2024), (Obalalu AM et al., 2023)).

An examination of the role of solar radiation on farms reveals more than a source of power. Instead, it will be about opening pathways to sustainability and contributing to the Sustainable Development Goals (SDGs). Studies have shown that solar energy is not just surplus power; it also has environmental benefits and economic benefits. For example, solar power irrigation systems have been found to reduce water consumption and increase crop yields (E Cai et al., 2026) (Panda SN. et al, 2024), which relieves concerns about food shortages (Y Cai et al., 2021)(Panda SN et al., 2024). In addition, these systems play a part in reducing greenhouse gas production and align with worldwide initiatives on sustainability (Bryan E Escoto et al., 2024). Another thread that keeps slipping in rural areas is how solar technology is remaking rural areas. Roy P et al. (2025) revealed that, in solar-using households, farmers can decrease their demand for conventional or informal means such as fuel wood, kerosene, and cow dung and can access new markets for eco-friendly products. This type of transition provides local farmers with inexpensive energy and support for sustainable standards, from smallholder agriculture to release, which are global development objectives (M S Sujatha et al., 2024). Harris et al. (2024) and Panda SN et al. (2024) argued that without the required skills and training, the potential for solar power is wasted. In many cases, the sharing of know-how is considered critical to ensuring that such systems work well on the ground. An examination of research methods in this field revealed a variety of methods and forms of writing. RRoy P et al. (2025) and (M S Sujatha et al. (2024) used a mixed-method approach, which is a combination of hard data and stories from the field, providing data and flavors of technology. Lifecycle assessments are also now widely used to demonstrate not only environmental positives but also areas with less positive effects (Harris I et al., 2024), (Panda SN et al., 2024)). These various approaches provide a more comprehensive understanding of how solar power belongs to sustainable farming.

Panda SN et al. (2024) and Bryan E Escoto et al. (2024) argued that solar power is the heart of agricultural practices and is crucial for sustainability and achieving the SDGs. This view goes hand in hand with findings that underscore how critical community support and solid policy backing are to make solar practical on farms. In many cases, the benefits of solar technology may not be equally accessible to everyone, especially in underprivileged rural areas. Significant investments and ongoing maintenance needs can be real stumbling blocks for smaller, marginalized farmers (M S Sujatha et al., 2024) (Harris et al., 2024).On the other hand, sustainability transition theory, a framework that hints at gradual but transformative change, suggests that harnessing solar power could spark not only immediate improvements but also long-term shifts toward a greener agricultural system ((Panda SN et al., 2024), (E M B M Karunathilake et al., 2023), (Magarelli A et al., 2024)). Taken together, these perspectives create a rich, sometimes messy, picture of how solar energy might steer farming toward a more sustainable, inclusive future (Time A et al., 2024; Obalalu AM et al., 2023).

Nikoli et al. (2025) focused on zero net energy operation by using photovoltaic and ground source heat pumps (GSHPs). Their initial cost was high,and the payback period was 7.4 years, which is relatively low for zero net energy operation; however, the aim of reducing carbon emissions was achieved.

Xiao (2025) used radio frequency, light, wind, and water, and various activities can reduce energy usage and improve the efficiency of agricultural procedures. Biocompatible wireless sensors combined with artificial intelligence can increase productivity once the cost of production decreases in the future, which would widely spread across major streams of agriculture. Olomiyesan and Oyedum (2024) used HOMER software to stimulate the energy demand for 100 households in Kadura and Katsina, Nigeria, and the energy requirement was estimated to be 184.1 kWh. The comparison was performed for two grids: a diesel (standalone) generator and a wind-PV-diesel generator. The results revealed that although the tariff was lower for standalone workers in general, hybrid workers had a lower cost in rural regions.

Kimaro et al. (2024) reported that solar drying, which involves both passive and hybrid drying, is very useful, as it can aid in drying during sunshades (or) beyond sunny hours. These technologies are viable, as they improve efficiency, which in turn reduces cost. Solar dryers are also environmentally sound and help in climate change mitigation. They have a lower rate of adoption.

Wagner et al. (2024) reported that perceived usefulness and subjective norms are two factors of concern for the adaptiveness of agrivoltaics. The other factors include landscape changes and bureaucratic hurdles. The innovativeness of the farmers themselves is a key feature for them to try agrivoltaics.

Buisson et al. (2024) highlighted the importance of solar irrigation pumps in Bangladesh, such as household food security, dietary diversityand farm profitability, irrigation for paddies during diversity and farm profitability, and irrigation for paddies during the dry season, when factors beyond direct impact, such as simple impact, was seen as having a greater impact than simple economic benefit or climatic mitigation. The best model of a solar irrigation pump according to this study is a fee for service pumps.

Agaton and Guno (2024) studied a solar-powered irrigation system for small-scale farmers and reported that SPIS is economically feasible, with a cost–benefit of USD 556.26/ha, an NPV of USD 229.68/ha,an IRR of 12.49%, and a payback period of 5.58 years. Limitations include the acceptance(social) of electricity rates and the suggestion of dual usage of solar energy for houses and farms.

Ljubojev (2024) argued that solar energy-powered agriculture reduces long-term production costs. He argues that adaptability increased as the price decreased by 82% from 2010--2020. The EU plans to improve solar power production from 320 GW to 600 GW from 2025 to 2030 so that there would be major development in the solar ecosystem. The Law on the Use of Renewable Energy Sources(LURES) introduced key innovations such as market premiums, buyer-producer models, and guarantees of origin to incentivize small-scale, citizen-led renewable projects.

Khan et al. (2024) noted that the efficiency of solar adoption is heavily dependent on farm size, expenditure and location and that the lack of proper infrastructure and capacity-building programmesis a downside. The advantages include improved water quality and enhanced productivity.

Venkatesan and Cho (2024) advocated the use of optimal energy by utilizing a strategy of forecasting factors such as short, medium, and long intervals; temperature; and environmental fluctuations to maintain greenhouse conditions based on crops. The results of this study suggest that more trials should be conducted to optimize the model before practical application.

Gayathri et al. (2023) argued that the use of agrivoltaics improved agricultural efficiency. This research shows that the soil microclimate is improved along with solar electricity production. The crops utilized were cherry, lettuce, and bell pepper, which were found to be most useful in arid regions and to support other ecosystems, such as livestock and aquaponics, thus improving the overall socioeconomic conditions of the farmers.

Shams et al. (2023) proposed an integrated farming model to make the most use of solar irrigation. The proposed model is suitable mainly for the topography of Bangladesh.

The black Bengal goat, fish and agricultural crops should be reared to ensure food security and maximum land usage. Matuli et al. (2023) suggested that proper utilization of agrovoltiacs can reduce weed growth on agricultural land and algal growth in water bodies and allow for the dual use of land. Moerkerken (2023) stated that stable long-term policies are important for increasing the adoption of solar PV by Dutch farmers. Behavioral intentions and the perceived importance of renewable energy are two important driving factors. They suggest the use of a panel dataset for further exploration. Hussain et al. (2023) reported that by using a high-efficiency irrigation system, 6.6 million liters of diesel were saved, and 41% of the water usage was reduced. Microfinance and leasing options for small-scale farmers are essential for the wide reach of solar-powered irrigation systems. An improvement in allied fields, such as precision irrigation, would contribute positively to SPIS system adoption

Singla et al. (2023) reported that the use of an agrivoltaics system can influence the microclimatic and radiation received by plants; thus, the use of shade-tolerant varieties in rural environments can be highly beneficial for optimizing land use, as they can provide food security, climate adaptation and energy demand.Othman et al. (2023) suggested that the growth of herbal plants, especially*Misai*, *occurs*near solar panels, as these plants have cooling effects. The results revealed a 3% increase in DC energy output. This plant could also act as a secondary source of income. Modi (2022) does not support increasing the subsidies for solar products in agriculture, as they are not reflected in the results. He argues that the initial cost is very high for solar PV systems, which is very high for most Agri. For entrepreneurs, careful credit schemes rather than flat-out subsidies would prove beneficial.

Guno and Agaton (2022) studied the difference between diesel and solar powered pumps in the Philippines. The initial setup cost is very high for solar energy compared with diesel, as the NPV is positive and the payback period is 2.88 years. The economies of scale are true according to the study, as large farmers are more willing to adopt than smaller farmers are, as the expenditure for them through diesel is high.

Korkmaz and Doğan (2021) analyzed energy efficiency and agricultural productivity in Elazig, Turkey, cattle farm. The results revealed an energy yield of 1.6 million kWh (area of 850 $m^{2)}$ for a period of 10 years and a reduction of 1.64 million kg in carbon emissions with a payback period of 4.6 years.

Tariq et al. (2021) argued that the globe is moving toward a more energy-dependent society with higher requirements, so it will be inevitable for agriculture and allied activitiesto move toward more sustainable means of power; therefore, most farm machineries, newer technologies, should initially be developed on the basis of the sustainability model. Lefore (2021), solar-dependent agriculture is on the rise because of its high potential benefits. However, challenges remain in fields such as groundwater depletion, lack of data and ineffective governance. The factor to be given the most importance is access to information efficiency and equitable access to all farmers. Policy coordination and research need to be improved.

Choi et al. (2021) assessed the feasibility of solar allied agriculture through patchouli crops. The results showed that the electricity generated was sufficient for a model village but also reduced the carbon footprint, but the study revealed that the feasibility of this project is questionable, as it is not economically viable in Indonesia without government subsidies. It has an environmental impact, as it reduces deforestation and grid dependence for electricity.

Kata et al. (2021) suggested that younger farmers are more willing to adopt solar allied agriculture in Poland. The support of instruments for specific farm characteristics is a key factor for the further adoption of solar allied agricultural equipment. Pascaris et al. (2021) argued about agrivoltaics from the perspective of the solar industry and global food and energy in agriculture. The main challenge discussed here is local resistance to solar adaptation, which could be overcome by favorable environmental policies and community acceptance through the economic and environmental benefits of solar energy.

Ali (2021) compiled data from West African countries and concluded that renewable energy can increase agricultural value-added products, which could directly lead to an increase in greenhouse gas, as other fields have attempted to catch up to progress, so moderation of the rate of adoption is very much needed, along with regional integration. Desai et al. (2021) reported that the use of a solar-based smart grid microgrid (SSM) is more effective than the use of a diesel power energy stem, as the power storage is decentralized and the distance between the user and the power plant is decreased. The findings show that SSM is 33% cheaper in terms of the net present cost and energy cost.

Jaiyoung Cho et al. (2020) analyzed the feasibility of integrating solar panels in agriculture by comparing rain-protected regions with SM areas. The results show that grape cultivation in the solar module region results in faster germination by 1–2 days, but the quality decreases because of delayed grape coloring due to shading from the panel. However, the adjacent harvest matched the quality of the control crops; during this period,55 MWh of electricity was generated. Wang et al. (2020) examined the emission and ecological footprints of South Asian countries from 1990--2018 and reported that globalization and agricultural activities contributed to environmental degradation. This finding suggests that the integration of solar energy with agriculture could reduce the environmental impact, along with careful monitoring and tailored policies for individual farm requirements.

SDG goal attainment through solar energy

M. Rumbayan et al. (2025) discussed the impact of solar energy on SDGs, i.e., access to clean energy (SDG 7), as it offers decentralized, affordable and relatively reliable electricity and supports basic agriculture through it, and quality education (SDG 4),in which energy helps people without grid connections for education by providing lighting and power access in educational institutions. Good health and well-being (SDG 3) through medical storage, preservation, and medical equipment application. Climate action (SDG 13) reduces fossil fuel dependency. Decent work and economic growth (SDG 8) through the installation and maintenance of solar panels and allied appliances. Industry, innovation, and infrastructure (SDG 9) and sustainable cities and communities (SDG 11) are dependent mainly on solar energy, as it is the most reliable, sustainable, emission-free energy, and as the energy requirements rise in the projected future.

Cuppari et al. (2024) reported that agrovoltaic systems have an impact on SDG 2 (zero hunger), as they are involved in crop production, and SDG 7 (affordable and clean energy) lowers the emission of greenhouse gas and the variable cost. SDG 8(Decent Work and Economic Growth) and SDG 13(Climate Action) actively promote an alternative method involving energy production. Solar technology improvements and falling costs are important factors that need to be considered, as this denotes the scope of broader adaptability in the future, which has an enormous impact on the SDGs.

Conclusion

Finally, for the growth of solar-based technologies among farmers on a segment-wise basis, there is a need for more awareness and promotion among farmers by the government departments and other stakeholders to increase the adoption by farmers. This is an untapped area of research, with potential for scope of future research on recording the market data of various regions of the country, todeterminethe strategy that can be followed to make this sector grow. On the other hand, the small farmers, compared to the large farmers, have very low economies of scale, and real estate value is far higher for smaller farmers than for the medium or large farmers. This is why there is a slum in the adoption of solar power by the smaller farmers. Therefore, policymakers may formulate policies and programs for vulnerable and small farming that want to but do not participate in it as a result of their perceived usefulness and subjective norms. Making farmers aware about the importance of SDGs and handholding the farmers by government and other stakeholders in utilizing certain technologies is critical and will pave way for the attainment of SDGs.

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Appendix

Data sources

Ref. No	**Citation**	**Hyperlink**
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