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Solar Energy's Role in Achieving Sustainable Development Goals in Agriculture

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

The adoption of solar energy in agriculture has the potential to significantly contribute to achieving multiple Sustainable Development Goals (SDGs), particularly those related to clean energy access (SDG 7), sustainable economic growth (SDG 8), responsible consumption and production (SDG 12), and climate action (SDG 13). This review article examines the various applications of solar energy in agricultural practices, including irrigation, crop drying, greenhouse heating, and powering farm machinery. It analyzes the economic, environmental, and social benefits of transitioning to solar-powered agriculture, such as reduced reliance on fossil fuels, lower greenhouse gas emissions, improved energy security, and increased income for farmers. The article also discusses the challenges and barriers to widespread adoption, including high upfront costs, lack of awareness and technical expertise among farmers, and inadequate policy support. Through a comprehensive review of existing literature and case studies, this article highlights the immense potential of solar energy in transforming the agricultural sector and contributing to sustainable development. It concludes by emphasizing the need for concerted efforts from governments, international organizations, and the private sector to promote and facilitate the integration of solar energy in agriculture, particularly in developing countries where access to clean energy and sustainable farming practices are most crucial for achieving the SDGs.

Keywords: Solar energy; agriculture; sustainable development goals; renewable energy; climate change.

1. INTRODUCTION

The global agricultural sector faces numerous challenges in the 21st century, including the need to feed a growing population, adapt to the impacts of climate change, and reduce its environmental footprint [1]. At the same time, the United Nations' Sustainable Development Goals (SDGs) have set ambitious targets for achieving sustainable economic growth, reducing poverty and inequality, and protecting the planet [2]. In this context, the adoption of renewable energy technologies, particularly solar energy, in agriculture has emerged as a promising solution for addressing these challenges and contributing to the achievement of the SDGs [3].

Solar energy has the potential to transform agricultural practices by providing a clean, reliable, and affordable source of energy for various applications, such as irrigation, crop drying, greenhouse heating, and powering farm machinery [4]. The use of solar energy in agriculture can reduce reliance on fossil fuels, lower greenhouse gas emissions, improve energy security, and increase income for farmers, particularly in rural and remote areas where access to the electricity grid is limited [5].

However, despite the numerous benefits of solar-powered agriculture, its widespread adoption faces several challenges and barriers, including high upfront costs, lack of awareness and technical expertise among farmers, and inadequate policy support [6]. Overcoming these challenges requires concerted efforts from governments, international organizations, and the private sector to promote and facilitate the integration of solar energy in agriculture, particularly in developing countries where access to clean energy and sustainable farming practices are most crucial for achieving the SDGs [7].

This review article aims to provide a comprehensive overview of the role of solar energy in achieving sustainable development goals in agriculture. It examines the various applications of solar energy in agricultural practices, analyzes the economic, environmental, and social benefits of transitioning to solar-powered agriculture, and discusses the challenges and barriers to widespread adoption. Through a review of existing literature and case studies, the article highlights the immense potential of solar energy in transforming the agricultural sector and contributing to sustainable development.

2. SUSTAINABLE DEVELOPMENT GOALS AND AGRICULTURE

The United Nations' Sustainable Development Goals (SDGs), adopted in 2015, represent a global framework for achieving sustainable development by 2030 [8]. The 17 SDGs cover a wide range of social, economic, and environmental issues, including poverty, hunger, health, education, gender equality, clean water and sanitation, affordable and clean energy, decent work and economic growth, industry, innovation and infrastructure, reduced inequalities, sustainable cities and communities, responsible consumption and production, climate action, life below water, life on land, peace, justice and strong institutions, and partnerships for the goals [9].

Agriculture plays a crucial role in achieving several of these SDGs, particularly those related to ending poverty (SDG 1), achieving zero hunger (SDG 2), promoting sustainable economic growth and decent work (SDG 8), and ensuring sustainable consumption and production patterns (SDG 12) [10]. However, the agricultural sector also faces significant challenges in terms of its environmental impact, including greenhouse gas emissions, deforestation, soil degradation, and water scarcity [11].

The adoption of renewable energy technologies, particularly solar energy, in agriculture has the potential to address these challenges and contribute to the achievement of multiple SDGs [12]. For example, the use of solar-powered irrigation systems can improve access to water for crops, increase agricultural productivity, and reduce the environmental impact of farming, thereby contributing to SDG 2 (zero hunger), SDG 6 (clean water and sanitation), and SDG 15 (life on land) [13].

Similarly, the use of solar energy for crop drying and processing can reduce post-harvest losses, improve food security, and increase income for farmers, thereby contributing to SDG 1 (no poverty), SDG 2 (zero hunger), and SDG 8 (decent work and economic growth) [14]. The use of solar-powered greenhouses can extend the growing season, increase crop yields, and reduce the use of fossil fuels for heating, thereby contributing to SDG 7 (affordable and clean energy), SDG 12 (responsible consumption and production), and SDG 13 (climate action) [15].

Furthermore, the adoption of solar energy in agriculture can have significant social and economic benefits, particularly for rural communities in developing countries [16]. Access to clean and affordable energy can improve the quality of life for farmers and their families, reduce the time and labor required for farming activities, and create new opportunities for income generation, such as the sale of surplus energy to the grid or the development of agro-processing businesses [17].

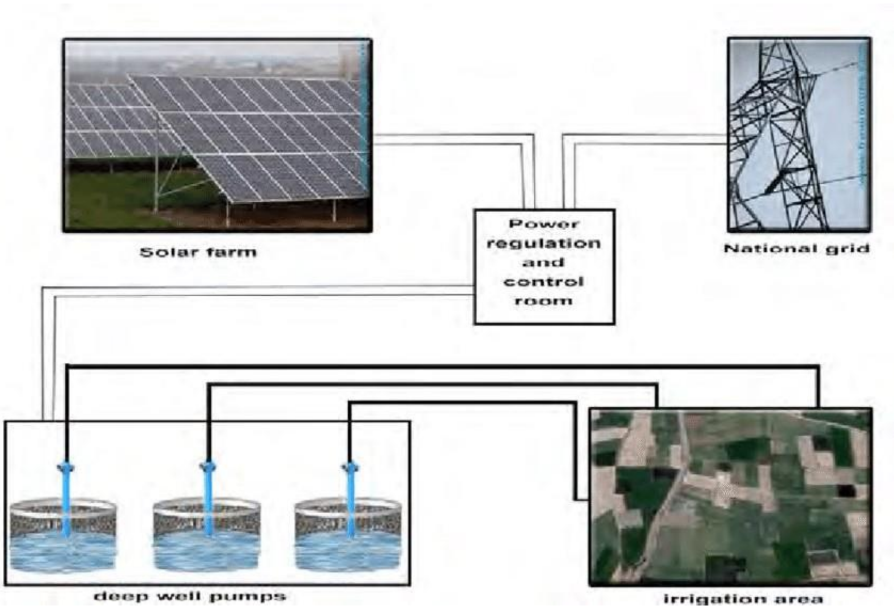

Fig. 1. Schematic diagram of a solar-powered irrigation system

However, achieving these benefits requires a comprehensive and integrated approach that takes into account the specific needs and contexts of different regions and communities [18]. This includes the development of appropriate policies and regulations, the provision of financial and technical support for farmers, and the promotion of awareness and capacity building among all stakeholders [19].

The following sections of this article will examine in more detail the various applications of solar energy in agriculture, the benefits and challenges of solar-powered agriculture, and the role of different stakeholders in promoting its adoption and achieving the SDGs.

3. APPLICATIONS OF SOLAR ENERGY IN AGRICULTURE

Solar energy has a wide range of applications in agriculture, from irrigation and crop drying to greenhouse heating and powering farm machinery [20]. This section will examine some of the most common and promising applications of solar energy in agriculture, highlighting their technical characteristics, benefits, and challenges.

3.1 Solar-powered Irrigation Systems

Irrigation is a critical component of agriculture, particularly in regions with limited or variable rainfall [21]. However, traditional irrigation systems, such as diesel-powered pumps, are often expensive, inefficient, and environmentally damaging [22]. Solar-powered irrigation systems offer a sustainable and cost-effective alternative, using photovoltaic (PV) panels to generate electricity for pumping water from wells, rivers, or reservoirs [23].

Solar-powered irrigation systems typically consist of PV panels, a pump, a controller, and a storage tank or reservoir [24]. The PV panels generate electricity during the day, which is used to power the pump and move water from the source to the storage tank or directly to the fields [25]. The controller regulates the flow of water based on the moisture content of the soil and the water requirements of the crops [26].

The benefits of solar-powered irrigation systems are numerous, including:

- Reduced energy costs: Solar energy is free and abundant, eliminating the need for expensive diesel fuel or electricity from the grid [27].
- Increased reliability: Solar-powered systems are not affected by power outages or fuel shortages, ensuring a consistent and reliable supply of water for crops [28].
- Improved water efficiency: The use of sensors and automated controllers can optimize the amount and timing of irrigation, reducing water waste and improving crop yields [29].
- Reduced greenhouse gas emissions: Solar-powered irrigation systems do not produce any emissions, contributing to climate change mitigation efforts [30].
- Increased income for farmers: The reduced energy costs and improved crop yields can increase the income and profitability of farmers, particularly in remote and off-grid areas [31].

However, solar-powered irrigation systems also face some challenges, including:

- High upfront costs: The initial cost of installing a solar-powered irrigation system can be high, particularly for smallholder farmers with limited access to finance [32].
- Technical complexity: The design, installation, and maintenance of solar-powered irrigation systems require specialized knowledge and skills, which may not be readily available in some regions [33].
- Water scarcity: In regions with limited water resources, the increased use of irrigation can exacerbate water scarcity and lead to conflicts over water use [34].
- Land requirements: Solar-powered irrigation systems require a certain amount of land for the installation of PV panels, which may compete with other land uses, such as crop production or grazing [35].

Despite these challenges, solar-powered irrigation systems have been successfully implemented in many regions of the world, particularly in Africa and Asia [36]. For example, in India, the government has launched a program to install 1.75 million solar-powered irrigation pumps by 2022, with the aim of reducing the use of diesel pumps and improving the livelihoods of farmers [37]. In sub-Saharan Africa, several initiatives, such as the Solar Irrigation for Agricultural Resilience (SoLAR) project, are promoting the adoption of solar-powered irrigation systems to improve food security and adapt to climate change [38].

3.2 Solar Crop Drying

Crop drying is an essential process in agriculture, particularly for preserving and storing grains, fruits, and vegetables [39]. Traditional crop drying methods, such as sun drying or diesel-powered dryers, are often inefficient, time-consuming, and environmentally damaging [40]. Solar crop drying offers a sustainable and cost-effective alternative, using solar energy to heat air and remove moisture from crops [41].

Solar crop dryers can be classified into two main types: passive and active [42]. Passive solar dryers rely on natural convection to circulate air through the crop, while active solar dryers use fans or blowers to force air through the crop [43]. Both types of solar dryers typically consist of a drying chamber, a solar collector, and a chimney or vent [44].

The benefits of solar crop drying include:

- Improved product quality: Solar drying can produce higher quality products than traditional sun drying, as it allows for better control over temperature, humidity, and airflow [45].
- Reduced post-harvest losses: Solar drying can reduce the amount of crop losses due to spoilage, pests, or weather damage, particularly in regions with high humidity or rainfall [46].
- Increased income for farmers: The improved product quality and reduced losses can increase the income and profitability of farmers, particularly for high-value crops such as spices, herbs, or medicinal plants [47].

Reduced environmental impact: Solar crop drying does not produce any emissions or waste, and can reduce the use of fossil fuels for traditional drying methods [48].

However, solar crop drying also faces some challenges, including:

- Dependence on weather conditions: Solar crop drying is dependent on the availability of sunlight, which can be variable and unpredictable in some regions [49].
- Technical complexity: The design and operation of solar crop dryers require specialized knowledge and skills, which may not be readily available in some regions [50].
- Limited capacity: Solar crop dryers typically have a limited capacity compared to industrial-scale dryers, which can limit their usefulness for large-scale farming operations [51].
- Cost: The initial cost of installing a solar crop dryer can be high, particularly for smallholder farmers with limited access to finance [52].

Despite these challenges, solar crop drying has been successfully implemented in many regions of the world, particularly in Asia and Africa [53]. For example, in Thailand, solar crop dryers have been used to dry a variety of crops, including rice, bananas, and chili peppers, with reported energy savings of up to 70% compared to traditional drying methods [54]. In Tanzania, a project funded by the United Nations Development Programme (UNDP) has promoted the use of solar crop dryers for drying fruits and vegetables, with the aim of reducing post-harvest losses and improving food security [55].

3.3 Solar Greenhouses

Greenhouses are structures used to grow crops in a controlled environment, allowing for year-round production and protection from pests and weather damage [56]. Traditional greenhouses rely on fossil fuels for heating and cooling, which can be expensive and environmentally damaging [57]. Solar greenhouses offer a sustainable and cost-effective alternative, using solar energy to regulate temperature and humidity [58].

Solar greenhouses typically consist of a transparent or translucent cover material, such as glass or plastic, that allows sunlight to enter and trap heat inside [59]. The trapped heat is then used to warm the air and soil, creating a favorable environment for plant growth [60]. Solar greenhouses can also incorporate other technologies, such as thermal storage materials, insulation, or ventilation systems, to optimize the growing conditions [61].

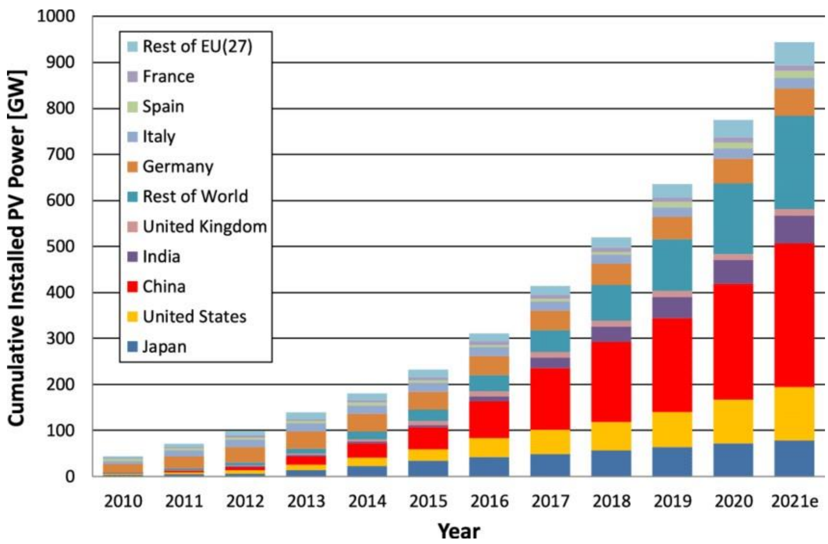

Fig. 2. Global installed capacity of solar PV in agriculture (2010-2020)

The benefits of solar greenhouses include:

- Extended growing season: Solar greenhouses can extend the growing season and allow for year-round production, particularly in regions with cold or variable weather [62].
- Increased crop yields: The controlled environment of solar greenhouses can increase crop yields and quality, as it allows for optimal growing conditions and protection from pests and diseases [63].
- Reduced energy costs: Solar greenhouses can reduce the use of fossil fuels for heating and cooling, leading to significant energy savings and reduced operating costs [64].
- Improved water efficiency: Solar greenhouses can incorporate technologies such as drip irrigation or hydroponics, which can reduce water use and improve water efficiency compared to traditional farming methods [65].

However, solar greenhouses also face some challenges, including:

- High upfront costs: The initial cost of constructing a solar greenhouse can be high, particularly for large-scale operations or regions with limited access to materials and labor [66].
- Technical complexity: The design and operation of solar greenhouses require specialized knowledge and skills, which may not be readily available in some regions [67].
- Limited crop diversity: Solar greenhouses are typically used for high-value crops such as vegetables, fruits, or flowers, which may limit their usefulness for other types of crops or farming systems [68].
- Dependence on weather conditions: Solar greenhouses are still dependent on the availability of sunlight, which can be variable and unpredictable in some regions [69].

Despite these challenges, solar greenhouses have been successfully implemented in many regions of the world, particularly in Europe, North America, and Asia [70]. For example, in China, solar greenhouses have been used to grow a variety of crops, including tomatoes, cucumbers, and strawberries, with reported energy savings of up to 80% compared to traditional greenhouses [71]. In the United States, several companies, such as Ceres Greenhouse Solutions and Nexus Greenhouse Systems, offer commercial-scale solar greenhouses for a variety of applications, from urban farming to cannabis cultivation [72].

3.4 Solar-powered Farm Machinery

Farm machinery, such as tractors, harvesters, and processing equipment, is essential for modern agriculture, but can be expensive and environmentally damaging to operate due to their reliance on fossil fuels [73]. Solar-powered farm machinery offers a sustainable and cost-effective alternative, using solar energy to power electric motors or hybrid systems [74].

Solar-powered farm machinery can take many forms, from small-scale electric tools such as pruners and shears, to large-scale machinery such as tractors and combines [75]. Solar-powered tractors, for example, typically use a combination of solar panels, batteries, and electric motors to provide power for traction and implements [76]. Some solar-powered tractors also incorporate regenerative braking systems, which can capture and store energy from braking to extend the range and efficiency of the vehicle [77].

The benefits of solar-powered farm machinery include:

- Reduced fuel costs: Solar-powered machinery can significantly reduce or eliminate the use of fossil fuels, leading to lower operating costs and increased profitability for farmers [78].
- Reduced emissions: Solar-powered machinery produces zero emissions during operation, contributing to climate change mitigation efforts and improving air quality in rural areas [79].
- Increased energy independence: Solar-powered machinery can reduce dependence on fossil fuel imports and increase energy security for farmers and rural communities [80].
- Improved health and safety: Solar-powered machinery can reduce exposure to harmful emissions and noise, improving the health and safety of farmers and workers [81].

However, solar-powered farm machinery also faces some challenges, including:

- High upfront costs: The initial cost of purchasing solar-powered machinery

However, solar-powered farm machinery also faces some challenges, including:

High upfront costs: The initial cost of purchasing solar-powered machinery can be high, particularly for large-scale equipment such as tractors or combines [82]. This can be a significant barrier for farmers, especially in developing countries or regions with limited access to financing [83].

Limited power and range: Solar-powered machinery may have limited power and range compared to traditional fossil fuel-powered equipment, particularly for heavy-duty tasks such as tillage or harvesting [84]. This can limit their usefulness for some farming operations or require the use of hybrid systems that combine solar power with other energy sources [85].

Dependence on weather conditions: Solar-powered machinery is dependent on the availability of sunlight, which can be variable and unpredictable in some regions [86]. This can limit their reliability and require the use of backup power sources or energy storage systems [87].

Technical complexity: The design, installation, and maintenance of solar-powered machinery require specialized knowledge and skills, which may not be readily available in some regions [88]. This can lead to issues with performance, reliability, and safety if the equipment is not properly designed or maintained [89].

Despite these challenges, solar-powered farm machinery has been successfully implemented in many regions of the world, particularly in Europe and North America [90]. For example, in Germany, several companies, such as Fendt and John Deere, have developed solar-powered tractors and other machinery for use in agriculture and forestry [91]. In the United States, startups such as Solectrac and Electric Tractor Corp are developing all-electric tractors powered by solar energy, with the aim of reducing emissions and improving the sustainability of farming [92].

4. BENEFITS OF SOLAR-powered AGRICULTURE

The adoption of solar energy in agriculture can provide a wide range of benefits, from economic and environmental to social and health-related [93]. This section will examine some of the most significant benefits of solar-powered agriculture, highlighting their potential contributions to sustainable development and the achievement of the SDGs.

4.1 Economic Benefits

Reduced energy costs: One of the most significant economic benefits of solar-powered agriculture is the reduction in energy costs for farmers [94]. By using solar energy to power irrigation systems, crop dryers, greenhouses, and machinery, farmers can reduce or eliminate their reliance on fossil fuels and grid electricity, which can be expensive and subject to price volatility [95]. This can lead to significant savings on energy bills and increased profitability for farmers, particularly in regions with high energy costs or limited access to reliable electricity [96].

Increased productivity and income: Solar-powered agriculture can also increase the productivity and income of farmers by enabling them to grow crops more efficiently and effectively [97]. For example, solar-powered irrigation systems can provide a reliable and consistent supply of water for crops, reducing the risk of drought or water stress and increasing crop yields [98]. Solar-powered greenhouses can extend the growing season and allow for the cultivation of high-value crops, such as vegetables or herbs, in regions with limited or variable sunlight [99]. Solar-powered crop dryers can improve the quality and value of crops by reducing post-harvest losses and enabling farmers to store and sell their products for longer periods [100].

Job creation and economic development: The adoption of solar-powered agriculture can also create new jobs and stimulate economic development in rural areas [101]. The installation, maintenance, and operation of solar-powered systems require skilled labor, which can provide employment opportunities for local communities [102]. The increased productivity and income from solar-powered agriculture can also stimulate demand for goods and services in rural areas, supporting the growth of local businesses and economies [103].

4.2 Environmental Benefits

Reduced greenhouse gas emissions: One of the most significant environmental benefits of solar-powered agriculture is the reduction in greenhouse gas emissions associated with traditional farming practices [104]. By replacing fossil fuels with solar energy, farmers can reduce their carbon footprint and contribute to global efforts to mitigate climate change [105]. For example, a study by the National Renewable Energy Laboratory (NREL) in the United States found that the adoption of solar-powered irrigation systems could reduce greenhouse gas emissions by up to 80% compared to traditional diesel-powered systems [106].

Reduced water usage and improved water quality: Solar-powered agriculture can also reduce water usage and improve water quality by enabling more efficient and sustainable irrigation practices [107]. Solar-powered irrigation systems can be equipped with sensors and automated controls that optimize the timing and amount of water delivered to crops, reducing water waste and improving crop yields [108]. Solar-powered desalination systems can provide a sustainable source of fresh water for irrigation in regions with limited or contaminated water resources, reducing the pressure on groundwater and surface water supplies [109].

Improved soil health and biodiversity: Solar-powered agriculture can also improve soil health and biodiversity by reducing the use of chemical fertilizers and pesticides [110]. Solar-powered systems can be used to power precision agriculture technologies, such as variable rate application of fertilizers or targeted spraying of pesticides, which can reduce the amount of chemicals used and minimize their impact on soil and water resources [111]. Solar-powered agriculture can also support the adoption of conservation tillage practices, such as no-till or cover cropping, which can improve soil structure, reduce erosion, and increase biodiversity [112].

4.3 Social and Health Benefits

Improved energy access and quality of life: Solar-powered agriculture can improve energy access and quality of life for rural communities, particularly in developing countries where access to electricity is limited or unreliable [113]. By providing a sustainable and affordable source of energy for farming and household uses, solar-powered systems can reduce the time and labor required for tasks such as water collection, cooking, and lighting, freeing up time for education, income-generating activities, and leisure [114]. Solar-powered systems can also improve the health and safety of rural communities by reducing exposure to indoor air pollution from traditional cooking and lighting sources, such as kerosene lamps or wood stoves [115].

Improved food security and nutrition: Solar-powered agriculture can also improve food security and nutrition by increasing the availability and affordability of fresh, nutritious foods [116]. Solar-powered irrigation systems and greenhouses can enable the cultivation of a wider variety of crops, including fruits and vegetables, in regions with limited or variable water and sunlight [117]. Solar-powered crop dryers and storage systems can reduce post-harvest losses and improve the quality and safety of food products, particularly in regions with limited access to refrigeration or processing facilities [118].

Empowerment of women and marginalized communities: Solar-powered agriculture can also empower women and marginalized communities by providing new opportunities for income generation and decision-making [119]. In many developing countries, women play a critical role in agriculture and food production, but often face barriers to accessing resources and markets [120]. Solar-powered systems can provide women with access to energy and water for farming and household uses, reducing their time and labor burden and enabling them to participate more fully in economic and social activities [121]. Solar-powered agriculture can also provide new opportunities for youth and other marginalized groups to engage in farming and agribusiness, supporting the development of more inclusive and equitable food systems [122].

5. CHALLENGES AND BARRIERS TO ADOPTION

Despite the numerous benefits of solar-powered agriculture, there are also significant challenges and barriers to its widespread adoption, particularly in developing countries and regions with limited access to resources and infrastructure [123]. This section will examine some of the most significant challenges and barriers to the adoption of solar-powered agriculture, highlighting the need for policy, financial, and technical support to overcome them.

5.1 Economic and Financial Barriers

High upfront costs: One of the most significant barriers to the adoption of solar-powered agriculture is the high upfront cost of purchasing and installing solar-powered systems [124]. While the cost of solar panels and other components has decreased significantly in recent years, the initial investment required for a solar-powered irrigation system, greenhouse, or tractor can still be prohibitive for many farmers, particularly smallholder farmers in developing countries [125]. This can limit the ability of farmers to adopt solar-powered technologies, even if they are aware of their potential benefits [126].

Limited access to financing: Another significant barrier to the adoption of solar-powered agriculture is the limited access to financing for farmers, particularly in developing countries [127]. Many farmers lack collateral or credit history, making it difficult for them to access loans or other forms of financing to purchase solar-powered systems [128]. This can limit the ability of farmers to invest in solar-powered technologies, even if they are willing and able to do so [129].

Lack of government support and incentives: The lack of government support and incentives for solar-powered agriculture can also be a significant barrier to its adoption [130]. In many countries, there are limited policies or programs in place to promote the use of renewable energy in agriculture, such as subsidies, tax incentives, or feed-in tariffs [131]. This can make it difficult for farmers to justify the upfront cost of investing in solar-powered systems, particularly if they are not guaranteed a return on their investment [132].

5.2 Technical and Infrastructural Barriers

Limited technical expertise and support: The limited availability of technical expertise and support for solar-powered agriculture can also be a significant barrier to its adoption [133]. Many farmers lack the knowledge and skills required to design, install, and maintain solar-powered systems, particularly in developing countries where access to education and training is limited [134]. This can lead to issues with system performance, reliability, and safety, which can discourage farmers from adopting solar-powered technologies [135].

Inadequate infrastructure and supply chains: The inadequate infrastructure and supply chains for solar-powered agriculture can also be a significant barrier to its adoption [136]. In many developing countries, there is limited access to reliable electricity grids, roads, and other infrastructure required to support the installation and maintenance of solar-powered systems [137]. There may also be limited availability of spare parts, components, and other supplies required for the operation and maintenance of solar-powered systems, which can increase the cost and complexity of adopting these technologies [138].

Limited data and information: The limited availability of data and information on the performance and benefits of solar-powered agriculture can also be a barrier to its adoption [139]. Many farmers lack access to reliable and accurate information on the costs, benefits, and risks of solar-powered technologies, which can make it difficult for them to make informed decisions about whether to adopt these technologies [140]. There may also be limited data on the specific applications and configurations of solar-powered systems that are most suitable for different regions, crops, and farming systems, which can limit the effectiveness and efficiency of these technologies [141].

5.3 Social and Cultural Barriers

Resistance to change and new technologies: One of the most significant social and cultural barriers to the adoption of solar-powered agriculture is the resistance to change and new technologies among some farmers and communities [142]. In many traditional farming communities, there may be a strong attachment to existing practices and technologies, which can make it difficult to introduce new and unfamiliar technologies such as solar-powered systems [143]. There may also be concerns about the reliability, safety, and long-term viability of these technologies, which can discourage farmers from adopting them [144].

Limited awareness and education: The limited awareness and education about solar-powered agriculture can also be a significant barrier to its adoption [145]. Many farmers and communities may not be aware of the potential benefits and applications of solar-powered technologies, particularly in developing countries where access to information and education is limited [146]. This can limit the demand for these technologies and make it difficult to build the necessary support and infrastructure for their adoption [147].

Gender and social inequalities: Gender and social inequalities can also be significant barriers to the adoption of solar-powered agriculture, particularly in developing countries [148]. Women and marginalized groups may face additional barriers to accessing resources, information, and decision-making power, which can limit their ability to adopt and benefit from solar-powered technologies [149]. There may also be cultural and social norms that restrict the participation of women and marginalized groups in certain farming activities or decision-making processes, which can further limit their ability to adopt and benefit from these technologies [150].

To overcome these challenges and barriers, there is a need for comprehensive and integrated approaches that address the economic, technical, and social dimensions of solar-powered agriculture [151]. This may include the development of policies and programs to provide financial and technical support for farmers, the strengthening of infrastructure and supply chains, the promotion of awareness and education about solar-powered technologies, and the empowerment of women and marginalized groups to participate in and benefit from these technologies [152].

6. CASE STUDIES

This section presents three case studies of successful solar-powered agriculture projects in different regions of the world, highlighting their key features, benefits, and lessons learned. The case studies demonstrate the potential of solar-powered agriculture to contribute to sustainable development and the achievement of the SDGs, while also illustrating the challenges and opportunities for scaling up these technologies in different contexts.

6.1 Case Study 1: Solar-Powered Irrigation in India

India is one of the world's largest producers of agricultural products, but also faces significant challenges related to water scarcity, energy access, and rural poverty [153]. To address these challenges, the government of India has launched a number of initiatives to promote the adoption of solar-powered irrigation systems, including the Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM) scheme [154].

The PM-KUSUM scheme aims to install 2.75 million solar-powered irrigation pumps by 2022, with a total capacity of 30.8 gigawatts [155]. The scheme provides subsidies and incentives for farmers to purchase and install solar-powered pumps, as well as technical assistance and training for the operation and maintenance of these systems [156].

One example of a successful solar-powered irrigation project in India is the Dhundi Solar Pump Irrigators' Cooperative in Gujarat [157]. The cooperative, which was established in 2016 with support from the International Water Management Institute (IWMI) and the Gujarat Energy Research and Management Institute (GERMI), consists of six farmers who have installed solar-powered pumps to irrigate their fields [158].

The cooperative has reported significant benefits from the adoption of solar-powered irrigation, including:

- Reduced energy costs: The farmers have reported savings of up to 50% on their energy bills, as they no longer need to rely on diesel pumps or grid electricity for irrigation.
- Increased crop yields: The farmers have reported increases in crop yields of up to 30%, as they are able to provide more reliable and consistent irrigation to their crops.
- Improved water efficiency: The solar-powered pumps are equipped with sensors and automated controls that optimize the timing and amount of water delivered to the crops, reducing water waste and improving water use efficiency.
- Increased income: The farmers have reported increases in income of up to 50%, as they are able to sell surplus energy generated by the solar panels back to the grid, providing an additional source of revenue.

The success of the Dhundi cooperative has inspired the development of similar solar-powered irrigation projects in other parts of India, demonstrating the potential for these technologies to contribute to sustainable agriculture and rural development.

6.2 Case Study 2: Solar-Powered Greenhouses in China

China is the world's largest producer of vegetables, but also faces significant challenges related to land scarcity, water stress, and environmental degradation. To address these challenges, the Chinese government has promoted the development of solar-powered greenhouses as a way to increase the efficiency and sustainability of vegetable production.

Solar-powered greenhouses in China typically consist of a passive solar design, with a south-facing glazed wall and a north-facing insulated wall, which allows for the collection and storage of solar energy during the day and the release of heat at night. The greenhouses also incorporate other energy-saving features, such as thermal curtains, natural ventilation, and energy-efficient lighting and heating systems.

One example of a successful solar-powered greenhouse project in China is the Lufa Farms greenhouse in Shanghai. The greenhouse, which was established in 2014, covers an area of 7,000 square meters and produces over 50 varieties of vegetables, herbs, and microgreens.

The Lufa Farms greenhouse has reported significant benefits from the adoption of solar-powered technologies, including:

- Reduced energy costs: The greenhouse uses passive solar design and energy-efficient systems to reduce its energy consumption by up to 50% compared to conventional greenhouses.
- Increased crop yields: The greenhouse is able to produce up to 10 times more vegetables per unit area than conventional field agriculture, due to the optimized growing conditions and the use of hydroponic systems.
- Improved water efficiency: The greenhouse uses a closed-loop irrigation system that recycles water and nutrients, reducing water consumption by up to 90% compared to conventional agriculture.
- Reduced environmental impact: The greenhouse produces no agricultural runoff or waste, and uses no synthetic pesticides or fertilizers, reducing its environmental impact compared to conventional agriculture.

The success of the Lufa Farms greenhouse has inspired the development of similar solar-powered greenhouse projects in other parts of China and around the world, demonstrating the potential for these technologies to contribute to sustainable urban agriculture and food security.

6.3 Case Study 3: Solar-Powered Tractors in Africa

Africa is home to some of the world's most rapidly growing populations and economies, but also faces significant challenges related to energy access, food security, and rural development.

To address these challenges, several initiatives have been launched to promote the adoption of solar-powered tractors and other agricultural machinery in Africa.
Solar-powered tractors are particularly well-suited to the African context, where many farmers lack access to reliable and affordable

sources of energy for agricultural mechanization. Solar-powered tractors can be used for a wide range of agricultural tasks, including plowing, harrowing, planting, and harvesting, and can significantly reduce the time and labor required for these tasks compared to manual methods.

One example of a successful solar-powered tractor project in Africa is the Solar Shamba project in Kenya. The project, which was launched in 2016 by the social enterprise Futurepump, aims to provide smallholder farmers with access to affordable and sustainable irrigation and mechanization solutions.

The Solar Shamba project has developed a range of solar-powered tractors and irrigation pumps that are specifically designed for the needs of smallholder farmers in Africa. The tractors are equipped with high-efficiency solar panels and batteries that can provide up to eight hours of continuous operation, and can be easily transported and maintained by farmers.

The Solar Shamba project has reported significant benefits from the adoption of solar-powered tractors, including:

Reduced labor and time requirements: The solar-powered tractors can significantly reduce the time and labor required for agricultural tasks, allowing farmers to cultivate larger areas of land and increase their productivity.

Increased crop yields: The solar-powered tractors can help farmers to improve the quality and consistency of their land preparation and planting, leading to increased crop yields and food security.

Reduced fuel costs: The solar-powered tractors eliminate the need for expensive and polluting diesel fuel, reducing the operating costs for farmers and improving their profitability.

Improved energy access: The solar-powered tractors provide farmers with access to reliable and affordable energy for agricultural mechanization, even in remote and off-grid areas.

The success of the Solar Shamba project has inspired the development of similar solar-powered tractor projects in other parts of Africa, demonstrating the potential for these technologies to contribute to sustainable agricultural mechanization and rural development.

7. CONCLUSION AND RECOMMENDATIONS

Solar-powered agriculture has the potential to make a significant contribution to sustainable development and the achievement of the SDGs, particularly in developing countries and regions with limited access to energy and resources. By providing farmers with access to affordable, reliable, and sustainable energy for irrigation, crop drying, greenhouse heating, and mechanization, solar-powered technologies can help to increase agricultural productivity, improve food security, reduce poverty, and protect the environment.

However, the adoption of solar-powered agriculture also faces significant challenges and barriers, including high upfront costs, limited access to financing and technical support, inadequate infrastructure and supply chains, and resistance to change among some farmers and communities. To overcome these challenges and realize the full potential of solar-powered agriculture, there is a need for concerted action and support from governments, international organizations, NGOs, and the private sector.

Based on the findings of this review, the following recommendations are made to promote the adoption and scaling up of solar-powered agriculture:

7.1 Policy and Institutional Support

Develop and implement policies and regulations to promote the adoption of solar-powered agriculture: such as subsidies, tax incentives, feed-in tariffs, and renewable energy targets.

Strengthen institutional capacity and coordination: Among government agencies, research institutions, and other stakeholders involved in the development and promotion of solar-powered agriculture.

Integrate solar-powered agriculture into national and regional agricultural development plans and strategies: To ensure that it is prioritized and supported as a key component of sustainable agricultural development.

7.2 Financial and Technical Support

Provide financial support and incentives for farmers to adopt solar-powered technologies, such as grants, loans, and microcredit schemes, to help overcome the high upfront costs and limited access to financing.

Strengthen technical support and extension services for farmers, to provide them with the knowledge, skills, and resources needed to adopt and maintain solar-powered technologies.

Invest in research and development of solar-powered technologies that are specifically designed for the needs and contexts of smallholder farmers in developing countries, such as low-cost, modular, and easily maintainable systems .

7.3 Awareness and Capacity Building

Raise awareness and understanding of the benefits and opportunities of solar-powered agriculture among farmers, policymakers, and the general public, through education, outreach, and communication campaigns.

Build the capacity of farmers, extension agents, and other stakeholders involved in the adoption and promotion of solar-powered agriculture, through training, workshops, and exchange programs.

Promote the sharing of knowledge, experiences, and best practices related to solar-powered agriculture among farmers, researchers, and practitioners, through networks, platforms, and events.

By implementing these recommendations and supporting the adoption and scaling up of solar-powered agriculture, it is possible to unlock the full potential of these technologies to contribute to sustainable development and the achievement of the SDGs. However, this will require a concerted and collaborative effort from all stakeholders involved, including governments, international organizations, NGOs, the private sector, and farmers themselves.

Table 1. Summary of the benefits and challenges of solar-powered agriculture

Benefits	Challenges
Reduced energy costs and increased profitability for farmers	High upfront costs and limited access to financing
Increased agricultural productivity and food security	Limited technical expertise and support for farmers
Reduced environmental impact and greenhouse gas emissions	Inadequate infrastructure and supply chains
Improved energy access and quality of life for rural communities	Resistance to change and new technologies among some farmers and communities
Empowerment of women and marginalized groups	Limited awareness and education about solar-powered agriculture
Contribution to the achievement of multiple SDGs	Gender and social inequalities that limit access to resources and decision-making power

Table 2. Examples of solar-powered agriculture technologies and their applications

Technology	Application	Benefits
Solar-powered irrigation systems	Pumping water for irrigation	Reduced energy costs, increased crop yields, improved water efficiency
Solar-powered crop dryers	Drying crops for storage and processing	Reduced post-harvest losses, improved crop quality, increased income for farmers
Solar-powered greenhouses	Controlling temperature and humidity for crop growth	Increased crop yields, reduced energy costs, improved water efficiency
Solar-powered tractors and machinery	Powering agricultural machinery for land preparation, planting, and harvesting	Reduced labor and time requirements, increased crop yields, reduced fuel costs

Table 3. Policy and institutional interventions to promote solar-powered agriculture

Intervention	Description	Examples
Subsidies and incentives	Providing financial support and incentives for farmers to adopt solar-powered technologies	Capital subsidies, interest-free loans, tax credits
Feed-in tariffs	Guaranteeing a fixed price for the excess electricity generated by solar-powered systems and fed back into the grid	Net metering, net billing, feed-in tariffs
Renewable energy targets	Setting targets for the share of renewable energy in the agricultural sector	National and regional renewable energy targets, renewable portfolio standards
Institutional coordination	Strengthening coordination and collaboration among government agencies, research institutions, and other stakeholders involved in the development and promotion of solar-powered agriculture	Inter-ministerial committees, public-private partnerships, multi-stakeholder platforms
Integration into agricultural development plans	Integrating solar-powered agriculture into national and regional agricultural development plans and strategies	National agriculture investment plans, regional agricultural development strategies

Table 4. Financial and technical interventions to promote solar-powered agriculture

Intervention	Description	Examples
Grants and loans	Providing financial support for farmers to purchase and install solar-powered technologies	Matching grants, concessional loans, revolving funds
Microcredit schemes	Providing small loans to farmers and rural communities to finance the adoption of solar-powered technologies	Group-based microcredit, individual microcredit, mobile money
Technical support and extension services	Providing farmers with the knowledge, skills, and resources needed to adopt and maintain solar-powered technologies	Farmer field schools, demonstration plots, mobile extension services
Research and development	Investing in research and development of solar-powered technologies that are specifically designed for the needs and contexts of smallholder farmers in developing countries	Low-cost and modular designs, locally manufactured components, user-friendly interfaces

Table 5. Awareness and capacity building interventions to promote solar-powered agriculture

Intervention	Description	Examples
Education and outreach	Raising awareness and understanding of the benefits and opportunities of solar-powered agriculture among farmers and other stakeholders	Farmer field days, radio and television programs, social media campaigns
Training and workshops	Building the capacity of farmers, extension agents, and other stakeholders involved in the adoption and promotion of solar-powered agriculture	Technical training, business management training, gender sensitization training
Knowledge sharing and exchange	Promoting the sharing of knowledge, experiences, and best practices related to solar-powered agriculture among farmers, researchers, and practitioners	Farmer-to-farmer exchange visits, online knowledge platforms, regional and international conferences

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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