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Renewable Energy in Agriculture: Enhancing Aquaculture and Post-Harvest Technologies with Solar and AI Integration

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

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ABSTRACT

Renewable energy, particularly solar energy, is an important component of sustainable agriculture because it provides energy-efficient and ecologically friendly alternatives to traditional techniques. AI reduced waste and produced predicted insights, improving agricultural operations. This review focuses on how solar energy and artificial intelligence are being used in aquaculture and post-harvest technologies. Aquaculture uses AI-driven systems to monitor real-time water quality and fish health, enhancing productivity by reducing mortality rates and minimizing environmental impact. AI algorithms optimize the utilization of sun dryers and cold storage units, reducing post-harvest

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losses by over 30% and ensuring high-quality produce by minimizing waste. The paper discusses the economic and environmental effects of various technologies, ranging from the high initial cost and existing constraints to the potential for decentralized energy networks and data-driven optimization. This analysis brings out the key trends, gaps, and future opportunities in integrating solar and artificial intelligence technologies for resilient, sustainable, and energy-efficient agriculture. The study establishes the groundwork for future developments in sustainable agriculture by highlighting the important implications for energy efficiency, climate resilience, and global food security.

Keywords: Renewable energy; Artificial Intelligence (AI); sustainable agriculture; aquaculture; post-harvest systems; Internet of Things (IoT).

1. INTRODUCTION

1.1 Background

Agriculture is the biggest sector in human life and economic activities and, therefore, depends strongly on energy. For decades now, fossil fuels have served as the major constituent meeting various sectors of agriculture's needs in terms of energy requirements (Kumar et al., 2023). The environmental impacts- greenhouse gas emissions and depletion of resources- triggered research into alternative sources of renewable energy. Solar energy has become one of the most promising alternatives for use in the agricultural sector, primarily due to its accessibility, affordability, and scalability (Mperejekumana et al., 2024a). Farmers around the globe are using solar-powered water pumps, greenhouse heating systems, among others. Aquaculture is an industry in agriculture, and it stands to gain quite significantly from renewable sources of energy. Renewable energy sources replace the energy that would have been consumed by the use of aeration, circulation, and monitoring systems created (Chen & Yu, 2024a).

1.2 Solar and AI Enhance Aquaculture

Precision agriculture has advanced greatly as a result of the automation of all-terrain vehicles for agricultural tasks made possible by machine learning and artificial intelligence vision technology (Padhiary, Saha, Kumar, et al., 2024). IoT-based pressure regulation systems offer advancements in precision spraying, ensuring efficiency and reduced wastage (Saha et al., 2023). Integrating IoT and AI in semi-autonomous sprayers revolutionizes modern farm mechanization (Padhiary, Tikute, Saha, et al., 2024). AI vision and machine learning continue to drive smart farming innovations, enhancing precision crop management and sustainability (Padhiary, 2024c). While solar energy happens to be clean and renewable, the integration of AI actually enhances its efficiency and applicability. The automation, predictive maintenance, and data-driven decisions through AI improve the efficiency of solar-powered systems. In aquaculture, AI-based systems monitor real-time water quality and optimize conditions for enhanced fish growth with reduced mortality rates (Mandal & Ghosh, 2024a). In the post-harvesting processes, AI algorithms can maintain ideal conditions in solar-powered cold storage units or optimize drying times in solar dryers. Together, these technologies significantly reduce food waste, enhance productivity, and thus contribute to food security around the world (Wani et al., 2023). Where there is a poor supply of electricity, and lots of post-harvest losses are prevalent, the role of solar and AI technologies is of immense importance in agriculture. Many developing countries are facing infrastructural problems that solar-powered systems can easily bypass. AI ensures that such systems are not only sustainable but smarter as well, responding to changing environmental conditions and the needs of the user.

1.3 Objectives and Scope of the Review

The article reviews the integration of renewable energy sources, especially solar energy, with AI-based technologies to improve aquaculture practices and post-harvest operations in agriculture. It discusses the role played by solar energy in sustainability, energy efficiency, and improving the operation of aquaculture systems and post-harvest technologies. Studying the application of solar energy in aquaculture, concerning such aspects as water aeration and temperature regulation in fish farms, and its application for post-harvest practices concerning drying, refrigeration, and storage to minimize food wastage and enhance preservation, and also by the use of artificial intelligence technologies in optimizing machine learning, predictive analytics, and automation on renewable energy-driven systems. The analysis will describe the barriers to the wide-scale application of these technologies and provide recommendations on how to overcome the technical, economic, and social barriers. The analysis will also provide international case studies of the most successful applications of these technologies, assess their impact on sustainability, and examine future trends and research in the area.

1.4 Methods and Algorithms

The optimization of synergy between solar energy and AI in renewable agriculture will improve efficiency and dependability by utilizing innovative algorithms and methodologies. Solar energy availability could be predicted by time-series forecasting models such as ARIMA and LSTM to guarantee peak hours for the operation of post-harvest dryers or aquaculture aeration systems (Salman et al., 2024). In order to maximize energy efficiency in systems that use solar energy to power drying or cold storage operations, RL agents can continually alter factors like airflow rates and pump speeds at any time. Also, IoT-based predictive maintenance can be powered by anomaly detection methods like autoencoders or isolation forests to stop solar energy systems from failing (Joshua et al., 2024). Biomass energy from solar systems or energy storage and consumption from wind can be utilized through hybrid optimization techniques, particularly genetic algorithms. Using combined crop grading and sorting using YOLO with AI vision algorithms, this technique not only significantly reduces energy waste but also boosts agricultural production (Paul et al., 2024). But as previously mentioned, if integration is successful, one powerful feature that can be applied to solar-AI-driven innovation for sustainable agriculture is immediately apparent.

2. AQUACULTURE AND POST-HARVEST SOLAR TECHNOLOGIES

The integration of solar technologies into the agricultural industry has unfolded tremendous potential to overcome energy-related problems while supporting sustainability. The solar energy-based systems have demonstrated high efficiency in aquaculture and post-harvesting activities, providing a stable source of clean power for these operations (Kar et al., 2023). This chapter looks into specific applications in aquaculture and post-harvest technologies, with their operational mechanisms, real benefits in practice, and implications on productivity and sustainability.

2.1 Photovoltaic Innovations in Aquaculture

Aquaculture operations require substantial energy inputs for aeration, water circulation, and quality monitoring. Solar energy systems meet these demands by providing cost-effective and renewable energy, especially in off-grid or rural settings.

Solar-Powered Aeration Systems: Oxygenation is critical for maintaining healthy aquatic environments (Ahmad et al., 2024a). Traditional aeration relies on electric or diesel-powered pumps, which are expensive and often inaccessible in remote areas. Solar-powered aerators eliminate these challenges by harnessing sunlight to maintain optimal oxygen levels (Behara, 2024). These systems reduce operational costs and ensure uninterrupted functionality, even during grid outages, when paired with battery storage.

Solar Water Pumps for Fish Farming: Water circulation is essential for nutrient distribution, waste management, and temperature control in fish and shrimp ponds. Solar water pumps replace conventional pumps, operating efficiently during daylight hours and storing excess energy for later use (Aliyu et al., 2018). These systems are particularly beneficial in regions with erratic power supplies, ensuring consistent water flow.

Case Studies in Practice: In Southeast Asia, solar-powered aeration systems have been widely adopted in shrimp farms, reducing energy costs by up to 30% and improving shrimp yields (Nguyen & Matsuhashi, 2019). In India, solar IoT devices monitor water quality in real time, enabling precise feeding and reducing fish mortality rates (Padhiary, Barbhuiya, Roy, et al., 2024). Integrating solar energy and AI in post-harvest technologies has led to revenue growth of up to 40% for smallholder farmers in Kenya, as documented in a 2023 study by the International Institute for Sustainable Development. These innovations highlight the potential for solar energy to enhance aquaculture efficiency and sustainability.

2.2 Solar Technologies in Post-Harvest Applications

Post-harvest processes, such as drying, cooling, and storage, play a crucial role in minimizing losses and preserving produce quality. Solar technologies provide innovative solutions for these energy-intensive tasks, offering cost-effective and environmentally friendly alternatives to traditional systems.

Solar Dryers: Traditional open-air drying methods expose crops to contamination, inconsistent drying, and spoilage. Solar dryers address these issues by providing controlled environments for drying grains, fruits, vegetables, and spices (EL-Mesery et al., 2022). Hybrid solar dryers, which incorporate thermal energy storage, ensure uninterrupted drying during cloudy weather. For instance, in India, farmers using solar dryers for turmeric and chili have achieved a 40% reduction in drying times, improving product quality and market value (Udomkun et al., 2020).

Solar-Powered Cold Storage Systems: Cold storage is essential for preserving perishable produce such as fruits, vegetables, and dairy products. Solar-powered refrigeration units provide consistent cooling, reducing spoilage and extending shelf life (Garcia et al., 2024). Advanced systems use phase-change materials to store thermal energy, ensuring reliable performance during night-time or cloudy periods. In Africa, solar-powered cold storage units have helped smallholder farmers reduce post-harvest losses by up to 50%, enabling them to access distant markets with higher prices (Amjad et al., 2023). The observed 40% revenue growth includes a 20% increase from reduced spoilage due to solar-powered cold storage and a 15% premium from higher-quality produce.

Solar-Powered Logistics Support: The integration of solar energy into mobile storage units ensures the safe transport of perishable goods. These units are equipped with smart cooling systems and IoT sensors, enabling real-time tracking of produce conditions during transit (Cil et al., 2022). This technology benefits farmers by reducing transportation losses and ensuring the delivery of high-quality produce to markets.

Solar-powered systems have diverse applications across aquaculture and post-harvest processes. Table 1 provides a comparative overview of these systems, highlighting their efficiency, scalability, and real-world case studies in various agricultural settings.

Table 1. Comparison of solar-powered aquaculture and post-harvest systems

Feature	Application	Efficiency	Scalability	Application	References
Solar-powered aeration	Oxygenation of water	High	Medium	Shrimp farms	(Roy et al., 2021)
Solar water pumps	Water pumping	Moderate	High	Fish ponds	(Chaibi et al., 2024)
Solar dryers	Drying crops	High	High	Grain drying	(Jha & Tripathy, 2021)
Solar cold storage	Cooling perishable	High	Medium	Vegetable storage	(Jarman et al., 2023a)
Solar-powered greenhouses	Climate control in farming	High	Medium	Tomato cultivation	(Ahmad et al., 2024b)
Solar desalination units	Freshwater for irrigation	Moderate	Low	Coastal farming	(Al-Addous et al., 2024)
Solar logistics systems	Food transport cooling	High	High	Perishable export chains	(Gallo et al., 2017)
Solar-powered fish feeders	Automated fish feeding	Moderate	Medium	Shrimp farms	(Padhiary, 2024a)

3. ROLE OF AI IN ENHANCING RENEWABLE ENRGY SYSTEMS IN AGRICULTURE

AI enabled renewable energy systems in agriculture have helped farmers by enhancing efficiency, reliability, and sustainability in aquaculture and post-harvest operations. It introduces precision, automation, and data-driven decision-making, demonstrating its transformative impact in these fields.

3.1 AI in Aquaculture

AI technologies have reshaped aquaculture by enabling precise monitoring, predictive analytics, and resource optimization (Mandal & Ghosh, 2024b). Integrated with solar-powered systems, AI enhances operational efficiency while reducing costs and environmental impact.

AI-Driven Monitoring of Water Quality: Solar-powered IoT devices in aquaculture farms collect real-time data on critical parameters such as temperature, pH, dissolved oxygen, and salinity (Hemal et al., 2024). Like electrochemical methods for in-situ soil analysis advance precision in fertilizer application (Padhiary, Kyndiah, Kumar, et al., 2024) and real-time plant identification using Python-based Raspberry Pi systems supports efficient crop management (Padhiary et al., 2023), AI algorithms process this data to provide actionable insights. For example, AI models can identify trends and detect anomalies that signal potential water quality issues, allowing farmers to take corrective measures proactively.

Feeding and Growth Optimization Forecasting: AI uses data on fish behaviour, water conditions, and historical feeding patterns to optimize feeding schedules. Automated feeding systems powered by solar energy ensure that fish receive the right amount of food at the right time, minimizing waste and improving growth rates (Gorjian et al., 2022). Predictive models can also forecast fish growth and harvest timelines, helping farmers plan better and reduce operational costs. AI-driven aquaculture systems enable precise monitoring and optimization of water quality and fish health. Fig. 1 illustrates the workflow of these systems, showcasing the integration of IoT devices, real-time data processing, and predictive analytics to improve aquaculture efficiency.

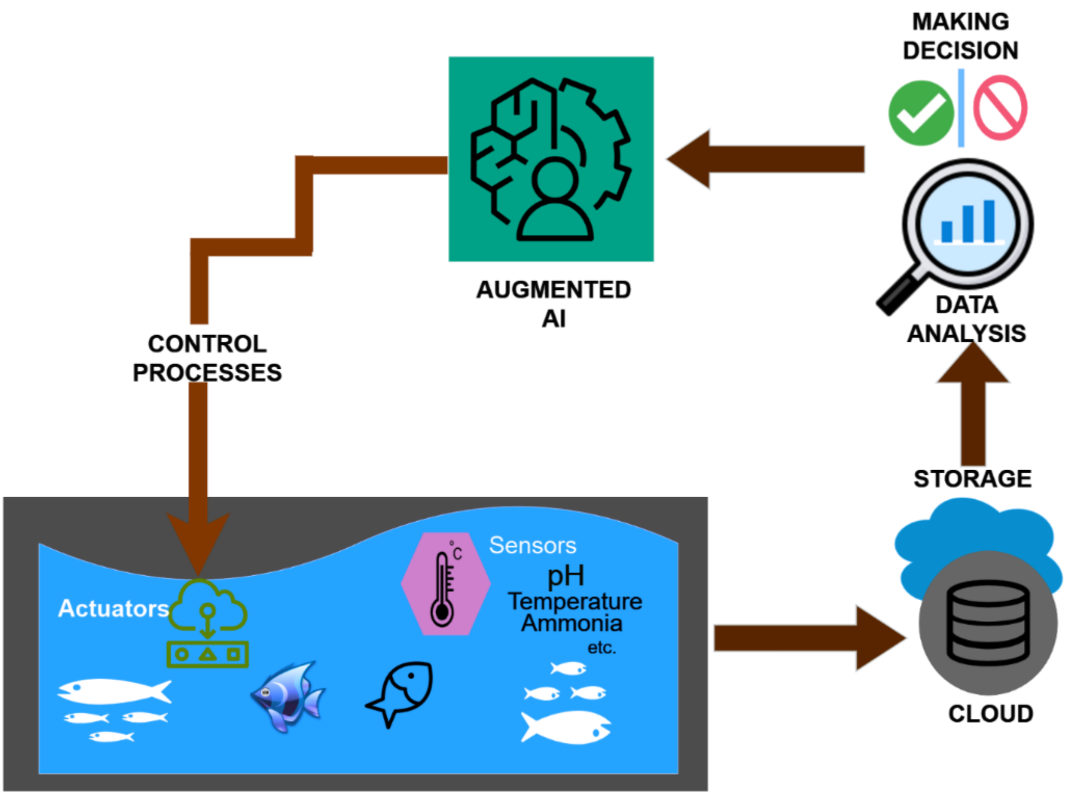

Fig. 1. AI-powered aquaculture systems' operation

3.2 AI in Post-Harvest Technologies

AI-driven solutions in post-harvest processes enhance the performance of solar-powered systems, enabling precise control, reduced waste, and improved product quality. AI-driven post-harvest technologies optimize operations, ensuring better resource utilization and quality control (Padhiary & Kumar, 2024b).

AI-Based Sorting and Grading Systems: Automated systems equipped with AI can sort and grade crops based on size, colour, and quality. Powered by solar energy, these systems operate sustainably even in off-grid regions (Aberilla et al., 2020). By ensuring uniform quality, AI-based sorting systems help farmers meet market standards and secure higher prices for their produce.

Predictive Maintenance for Solar Systems: AI enables predictive maintenance of solar-powered dryers and cold storage units by identifying potential system failures before they occur (Pandey et al., 2024). This reduces downtime and repair costs while extending the lifespan of the equipment. For instance, AI algorithms analyse energy consumption and panel efficiency to recommend maintenance actions.

Energy Optimization in Solar Dryers and Cold Storage: Solar dryers and cold storage units equipped with AI sensors monitor environmental conditions such as temperature, humidity, and sunlight intensity. AI dynamically adjusts system operations to optimize energy use (Um-e-Habiba et al., 2024). For example, during peak sunlight hours, a solar dryer might increase airflow to speed up drying, while at night, stored thermal energy is utilized efficiently under AI control. Incorporating AI into solar-powered systems for post-harvest logistics enhances operational efficiency and minimizes losses. This is illustrated in Fig. 2, which demonstrates the integration of AI-powered solar solutions in post-harvest supply chains.

3.3 Principal Effects of AI on Energy Efficiency

Enhanced Efficiency: AI significantly enhances the efficiency of solar energy systems in agriculture by optimizing their performance and reducing energy wastage. For example, AI algorithms process real-time data from sensors to determine the precise operational requirements of solar-powered devices. In aquaculture, AI can control aerators and pumps, ensuring they operate only, when necessary, based on water quality parameters such as oxygen levels (Lindholm-Lehto, 2023a). This precise control avoids energy overuse, increases the lifespan of equipment, and ensures that solar energy is utilized to its full potential.

Fig. 2. AI-powered solar integration in post-harvest logistics

Cost Savings: Predictive analytics powered by AI reduces operational costs by minimizing energy consumption, labour, and equipment downtime. AI-driven systems predict maintenance needs for solar panels and associated equipment, preventing unexpected breakdowns and costly repairs (Sayal et al., 2024). In post-harvest technologies, automated sorting, grading, and drying systems reduce the need for manual labour. By optimizing energy use in solar-powered cold storage units, AI helps farmers cut electricity expenses while preserving the quality of their produce, translating to reduced losses and increased profitability (Gouda & Duarte-Sierra, 2024).

Sustainability: AI improves the reliability of solar-powered systems, enabling farmers to transition to sustainable agricultural practices. By efficiently managing energy storage and distribution, AI ensures that solar systems provide consistent performance even during unfavourable weather conditions (He et al., 2022). This reduces reliance on fossil fuels, lowering greenhouse gas emissions. Additionally, AI-optimized solar technologies enable better resource management, such as reducing water wastage in aquaculture or preserving more produce during post-harvest storage, aligning with sustainable development goals. Farm automation and AI-driven systems reduce the environmental footprint of agriculture through optimized resource utilization (Padhiary, 2024b). AI and IoT integration in farm operations contribute to a sustainable ecosystem by minimizing agricultural waste (Padhiary, Roy, Dey, et al., 2024). Assessing the impact of industrial and agricultural activities on agro-ecosystems is critical for sustainable development (Padhiary & Kumar, 2024a).

3.4 Real World Cases

AI in Aquaculture (Norway): In Norway, fish farms have integrated solar-powered systems with AI to enhance water quality management and energy efficiency. IoT devices monitor parameters like dissolved oxygen, pH, and temperature, and AI algorithms analyse this data to automate aeration systems (Tsai et al., 2022). This reduces energy costs by ensuring that aerators operate only when needed. The optimized oxygen levels improve fish health and growth, leading to higher yields. This approach has proven especially beneficial for large-scale aquaculture operations aiming for sustainability and cost efficiency.

AI in Post-Harvest Technologies (Kenya): In Kenya, solar-powered cold storage units equipped with AI have transformed post-harvest processes for smallholder farmers (Jarman et al., 2023b). These systems monitor and maintain optimal temperature and humidity levels for storing perishable goods like vegetables and fruits. AI algorithms predict cooling needs based on the type and quantity of produce, as well as external environmental conditions. As a result, spoilage rates have dropped significantly, allowing farmers to sell their produce over an extended period. This has increased farmers' incomes by up to 40%, while the use of solar power has eliminated dependence on expensive and unreliable grid electricity (Shahsavari & Akbari, 2018).

4. INTEGRATED SOLAR AND AI SYSTEMS: A CASE STUDY APPROACH

This section explores the integration of solar technologies and AI systems in aquaculture, highlighting their potential to improve efficiency, sustainability, and productivity, addressing challenges and delivering economic and environmental benefits.

4.1 AI and Solar Synergy in Aquaculture

Together, solar power and AI work to optimize the aquaculture operation in order to reduce the costs. A fine example in this direction would be the use of solar-powered IoT devices equipped with AI analytics at fish and shrimp farms (Perez et al., 2024). These monitor the real-time water quality parameters, namely temperature, dissolved oxygen, and salinity, giving insights to farmers on how they can intervene and prevent or recover from oxygen depletion before any issue arises or the fish is subjected to death. Cases range from Southeast Asia, which made shrimp farming operations hugely better with solar-powered IoT systems. The farmers showed improvements of 20–30% of savings in energy costs by their productivity enhancement through AI-based monitoring combined with solar pumping and aeration (Mallareddy et al., 2023). More than that, they could remove the need for constant human presence by remote monitoring capabilities.

4.2 Synthetic intelligence and Solar Implementation for Post-Harvest Technologies

The integration of solar and AI enhances post-harvesting processes, such as drying and cold

Table 2. Economic and energy efficiency benefits of integrated solar and AI systems in agriculture

Parameter	Solar-only systems	AI-only systems	Integrated systems	References
Energy savings	30-50% compared to traditional methods	Minimal	50-70%	(Harvey, 2009)
Productivity improvement	10-20% due to improved energy access	20-30% via precise control and analytics	40-50%	(Benavente-Peces, 2019)
Environmental impact	Reduced carbon footprint	Indirect benefits	Significant reduction	(Mahapatra et al., 2021)
Maintenance costs	Low to Moderate	High	Moderate	(Semprini et al., 2016)
Operational flexibility	Fixed operational capacity	Adaptive but energy-dependent	Highly adaptive	(Mperejekumana et al., 2024b)
Scalability	Limited to energy availability	Dependent on data access	High across systems	(Lindholm-Lehto, 2023b)
Reliability	Weather-dependent	High for prediction models	Optimized via synergy	(Mandal & Ghosh, 2024c)

storage. For instance, AI algorithms can be integrated into solar dryers to monitor and control drying conditions in real time. In this case, AI adjusts drying times based on ambient temperature, humidity, and weather forecasts to ensure uniform products while minimizing energy usage (Hassoun et al., 2024). This integration has worked for India, where hybrid solar dryers with AI optimization have reduced the drying time for spices by 40%, fetching better market prices (Saha et al., 2024). For similar results, the solar-powered cold storage system, enhanced through AI, keeps the optimum storage conditions for perishables. AI-based predictive models enable forecasting storage demand with optimized energy consumption for controlled thermal storage during non-sunny days. Within Africa, solar-AI-based cold storage systems help cut post-harvest losses by up to 50% for crops, tomatoes and mangoes, increasing profitability of these crops for accessing higher-premium markets through such access technologies with these smallholder farmers.

4.3 Economic and Energy Efficiency Benefits of Integrated Systems

The integration of solar and AI technologies results in significant cost savings and energy efficiency. A study comparing traditional and solar-AI systems showed that energy consumption decreased by 25–40%, while operational efficiency increased by 30–50% (Chand et al., 2024). Traditional methods of post-harvest management yield an average growth of 10%, whereas solar- and AI-powered systems achieve a growth of 40%, representing a 300% improvement. Additionally, reduced reliance on grid power and diesel generators significantly lowers greenhouse gas emissions, aligning with global sustainability goals. The comparative analysis in Table 2 outlines the economic and energy efficiency advantages of integrating solar and AI systems. The data clearly show significant cost savings and enhanced productivity in agricultural operations compared to traditional methods.

5. DEVELOPMENTS IN AGRICULTURAL AUTOMATION AND ROBOTIC

Farming operations are being reshaped by agricultural automation and robotics, which allow for greater efficiency and adaptability across a spectrum of jobs and terrains. Modern precision agriculture relies heavily on automatic all-terrain vehicles (ATVs), which have become a game-changing technology that improves operations in a variety of challenging farming environments (Padhiary, Kumar, & Sethi, 2024; Padhiary, Sethi, & Kumar, 2024). The development of smarter farm equipment has been further accelerated by the combination of robotics, improved sensors, and the IoT (Rabha et al., 2024). By enabling real-time data collection, smooth task execution, and optimum performance, these integrated systems lower human labor costs and boost output. Additionally, the design and development of modular attachments for farming gear has benefited greatly from the introduction of 3D printing technology. Precision agriculture will become more efficient and versatile as a result of this invention, which makes it possible to develop affordable, adaptable equipment that are tailored to the unique requirements of different agricultural activities (Padhiary & Roy, 2024).

Beyond conventional farming, automation is having an impact on aquaculture, where fish farming methods are evolving by solar-powered and Internet of Things-enabled equipment. These developments enhance feeding precision, water quality control, and system sustainability in general, increasing yields while lessening their negative effects on the environment. Sorting, grading, and packaging are among the post-harvest processing tasks that are streamlined by the integration of robotics and AI. By reducing losses and guaranteeing higher-quality products, this increases the supply chain's sustainability and efficiency. The ground-breaking potential of robotics and artificial intelligence in agriculture is highlighted by these developments in automation, aquaculture, and post-harvest technology. These technologies are updating conventional methods, advancing sustainability, and propelling technological advancement in the agriculture industry by encouraging creativity across various sectors.

6. CHALLENGES AND OPPORTUNITIES

Aquaculture and post-harvest processes of agriculture will witness a revolution with the integration of renewable energy, primarily solar, and artificial intelligence (AI) (Mishra & Mohapatra, 2022). However, these carry drawbacks such as high upfront costs of initial installation, variability of the supply of solar power, scarcity of technical persons in rural areas, infrastructural facilities, maintenance of installations, long-term sustainability, policy issues, and vague regulatory frameworks. With all this, solar energy breaks dependence on fossil fuels, cost operations lowers, and reduces carbon emission in energy-intensive processes (Lewis, 2016). Aquaculture utilizes AI in improving efficiency by optimizing the feeding schedule through water quality monitoring, particularly by disease forecasting, and, at the post-harvest supply chain, through real-time monitoring with predictive analytics. Decentralized renewable energy systems, such as solar microgrids, are scalable and empower rural communities (Waseem et al., 2024). They support entrepreneurship through scalable options. Technological innovations, including low-cost energy storage and AI algorithms designed for agriculture, will increasingly make these systems accessible (Qazi et al., 2022). International cooperation and supportive policies are enabling scaling up for those solutions. Solutions would be largely taken over by the governments or the private sector, appropriate incentives, capacity building, or focused investments.

7. ETHICS IN AI APPLICATIONS: A CONSIDERATION

The application of generative AI in retail raises a wide range of new ethical concerns regarding the usage of customer data. There are significant privacy, security, and permission issues with building a sizable, detailed client database that would be utilized for suitable AI system training (Alkaeed et al., 2024). Sensitive information can be handled improperly or compromised in a variety of ways when it is not even sufficiently safeguarded. The hyper-personalization made possible by generative AI technology also has the drawback of allowing specialized profiles to be used to promote goods that may not ultimately be in the best interests of customers (Raut et al., 2024). It may imply that the balance would be unlawfully pushed toward the necessity of promoting innovation over the equally significant responsibility of safeguarding consumer rights. The process of transition will result in the creation of regulations pertaining to the application of artificial intelligence, with complete transparency about policy matters and strong protection of consumers' legal rights, as in any other market sector (Walter, 2024).

8. FUTURE PERSPECTIVES

Renewable energy in agriculture is poised to revolutionize the industry, addressing global challenges like food security, energy efficiency, and climate change through innovative technologies and research opportunities (Morkūnas et al., 2024).

8.1 Emerging Trends in Renewable Energy Technologies

Innovations in solar technology are poised to revolutionize agricultural systems further. Advanced photovoltaic (PV) materials, such as bifacial solar panels and perovskite solar cells, promise higher efficiency and lower costs (Verma, 2024). Solar energy storage solutions, including next-generation batteries and thermal storage, are addressing intermittency challenges, enabling 24/7 operations in aquaculture and post-harvest systems (Klokov et al., 2023). Additionally, decentralized solar microgrids are becoming more prevalent, empowering rural communities with reliable, off-grid energy solutions tailored to their needs.

8.2 AI Advancements for Sustainable Agriculture

AI technologies are advancing rapidly, offering greater precision and automation in agricultural processes (Bhat & Huang, 2021). Predictive analytics powered by AI can anticipate environmental fluctuations, optimize resource allocation, and enhance the resilience of farming systems. For example, machine learning models can improve the accuracy of weather forecasts and adjust solar-powered systems dynamically for maximum efficiency (Suanpang & Jamjuntr, 2024). AI-driven robotics, such as automated harvesting and drone-based crop monitoring, are also gaining traction, potentially reducing labour requirements and improving yields.

8.3 Integration of Emerging Technologies

New opportunities for agriculture converge in solar, AI, others, such as blockchain and IoT. It's here that blockchain can potentially make a difference in providing transparency and traceability along the supply chain (Grover et al., 2024). This is where IoT sensors using solar systems provide timely data on smarter decisions. Hybrid solar systems also attract more attention, considering heterogeneous regional energy needs as they combine both solar and other renewables, such as wind and bioenergy (Atawi et al., 2022). Moreover, AI-generated insights into biogenic nanoparticles and their applications in nanobiotechnology provide new opportunities for advancing agricultural practices, especially in utilizing the use of assets to encourage sustainability (Padhiary, Roy, & Dey, 2024).

8.4 Research Gaps and Future Directions

Despite significant progress, several gaps remain in the field. For example, there is a need for:

Affordable and Scalable Solutions: This research exactly focuses on the critical objective of significantly reducing the cost associated with solar panels, in addition to the advancements in AI technologies, which are intended to not only make such resources available but also accessible to small-scale farmers, who have previously been restrained from using such innovations (Lefore et al., 2021).

Localized Adaptations: Research often tends to be generalized on sustainable practices; however, in most areas, there are special climatic and socioeconomic conditions that demand particular solutions. For example, cloudy regions require systems for low-light conditions; poor regions need something affordable to build and maintain (Chen & Yu, 2024b). Such gaps demand adaptive models and technologies to address the needs of every region.

Enhanced Energy Storage: Current battery technologies used in solar-powered systems have limitations such as short lifespans, low efficiency, and high costs (Hasan et al., 2023). These constraints hinder the scalability and reliability of solar energy systems, particularly in areas with inconsistent sunlight. Future research should aim to improve energy storage systems by exploring advanced materials (e.g., solid-state batteries, supercapacitors) and designs that extend durability, increase energy density, and reduce production costs (Thomas et al., 2024). Such advancements could revolutionize off-grid energy solutions and enhance the viability of renewable energy worldwide.

Interdisciplinary Research: This integration between solar power and agriculture, along with smart grids, demands interdisciplinary collaboration. Combining energy systems, agricultural science, and computer science into one field allows for innovation such as solar-powered precision irrigation and AI-driven energy management (Edison, 2023). Such a model optimizes resources, increases efficiencies, and helps the world meet global challenges: food security and sustainable energy. The transition to data-driven agriculture is exemplified by emerging AI-based decision-making systems for farm operations (Hoque & Padhiary, 2024). Smart farming integrates AI, IoT, and automation to redefine agricultural practices in the context of renewable energy adoption (Padhiary, Roy, & Roy, 2024). As summarized in Table 3 identifies key areas such as cost reduction, scalability, and interdisciplinary collaboration, which are critical for future development.

Table 3. Emerging trends and research gaps in renewable energy and AI

Focus area	Emerging trends	Research gaps	Future directions	Impact	References
Solar energy	Advanced PV materials (e.g., bifacial panels, perovskite cells), improved storage solutions	High costs of advanced solar tech; limited scalability in small-scale farms	Development of low-cost, scalable solar systems tailored for smallholders	Enhanced energy efficiency and affordability	(Kefas et al., 2024)
Artificial intelligence	Predictive analytics, AI-driven robotics, dynamic optimization of solar-powered systems	Limited adaptation to region-specific needs; underdeveloped AI models for agriculture	Localized AI solutions, integration with IoT for precision farming	Increased productivity and resource use	(Oriekhoe et al., 2024)
Integrated systems	Hybrid solar systems combining wind, bioenergy, or other renewables for reliability	Lack of frameworks for multi-renewable integration; technical interoperability challenges	Hybrid systems designed for diverse energy needs and regional variations	Resilient and sustainable energy ecosystems	(Alaoui et al., 2024)
Technology convergence	IoT, blockchain for supply chain transparency, decentralized solar microgrids	Limited access to technology in rural areas; high costs for implementation	Accessible, low-cost IoT and blockchain solutions with supportive policies	Empowered rural communities and efficiency	(Kaur & Parashar, 2022)
Sustainability goals	Focus on low-carbon technologies, alignment with SDGs	Inadequate policies for large-scale adoption; lack of incentives for farmers	International collaboration and government incentives for scaling renewable and AI technologies	Reduced emissions, improved food security	(Streimikiene et al., 2024)
Energy storage	Innovations in batteries and thermal storage for 24/7 operations	Short lifespan and high costs of current storage solutions	Research into durable and efficient energy storage technologies	Consistent energy availability in off-grid areas	(Spataru & Bouffaron, 2016)
Interdisciplinary research	Collaboration across agriculture, energy, and computer science	Fragmented research approaches; insufficient funding for integrated projects	Promoting interdisciplinary initiatives for holistic advancements	Breakthroughs in agricultural sustainability	(Shafik, 2024)

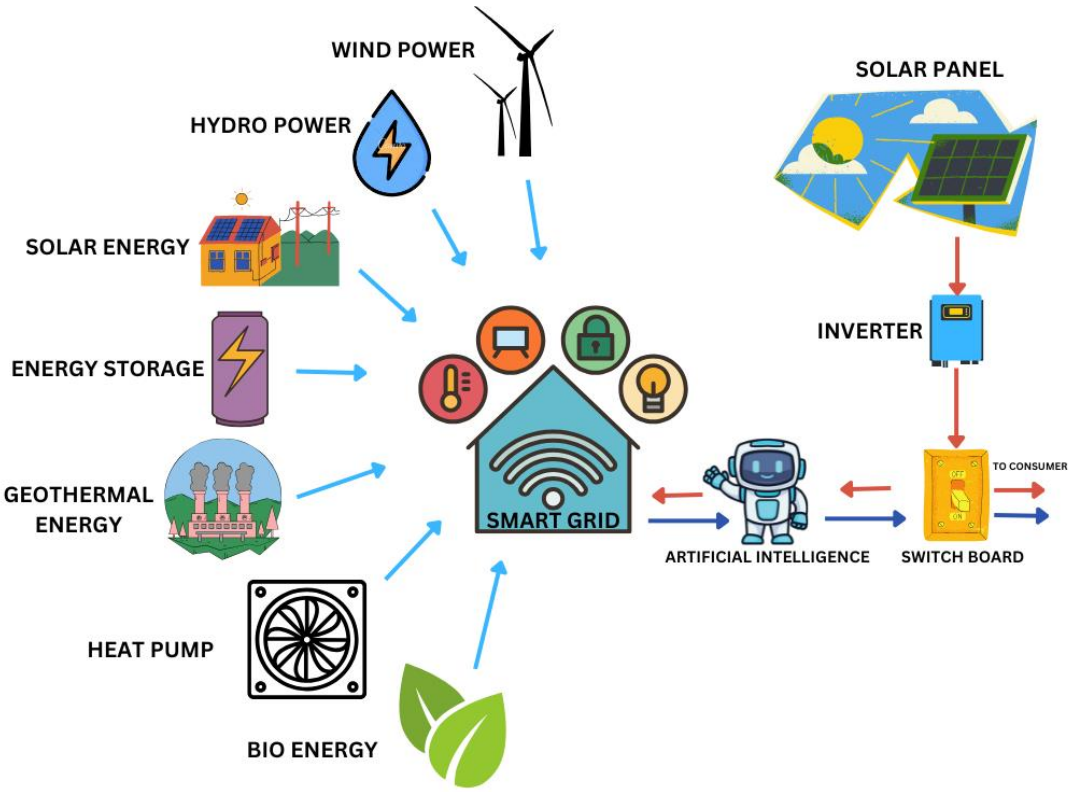

Fig. 3. AI-powered potential of industry for renewable energy and material development

8.5 Long-Term Vision

The long-term vision of the integration of solar and AI in agriculture will be a fully autonomous, energy-efficient farming ecosystem. This means that these systems should be completely dependent on renewable energy (Gupta et al., 2022). AI would control every process-from planting to harvesting-to logistics in post-harvest handling. This vision fits the overall goals for sustainable development and climate change mitigation around the world and presents a road towards a more resilient agriculture. The future potential of integrating AI with renewable energy systems in agriculture is substantial. Fig. 3 highlights the envisioned AI-driven advancements in renewable energy and material development, supporting the creation of fully autonomous and efficient agricultural systems (Padhiary and Rani, 2023; Padhiary and Saha, 2024).

9. CONCLUSION

Solar technologies and artificial intelligence have transformed the industry of aquaculture and post-harvest agriculture by integrating them. As compared to other sources of power, solar power is renewable, cost-effective, and environment-friendly. Artificial intelligence increases accuracy, productivity, and intelligent choice-making. Aquaculture solar-powered systems increase efficiency and reduce energy costs. Solar dryers and cold storage systems during post-harvest processes minimize spoilage and maximize agricultural produce quality to improve profitability and food security. AI-optimized solar systems minimize intermittency, energy wastage, and resource inefficiency while developing adaptive agricultural systems to face the challenges of climate change, increasing energy demand, and food loss. However, these include high upfront costs, technical skills scarcity, and the variable nature of solar energy. An integrated and cooperative methodology is important in the realization of the maximum potential that such technologies can exploit in global food systems.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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