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(Research Article)

Integration of renewable energy-powered cold storage solutions for reducing post-harvest food waste in rural agricultural areas

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Abstract

Post-harvest food loss remains a critical challenge in rural agricultural areas, exacerbated by inadequate storage facilities and unreliable energy access. This study develops and optimizes an advanced renewable energy-powered cold storage system tailored for rural settings, integrating solar and wind energy with phase change materials (PCMs) for efficient energy storage. The system incorporates Internet of Things (IoT)-based sensors and artificial intelligence (AI)-driven energy management to maintain optimal storage conditions and enhance energy efficiency. Field trials conducted in Lincolnshire, UK, and Appalachian regions of the US demonstrated significant reductions in post-harvest food loss by an average of 43.5%, extensions in produce shelf-life by up to 300%, and increased income for smallholder farmers by approximately 43%. The system also achieved an 80% reduction in greenhouse gas emissions compared to conventional diesel-powered systems. Economic analyses revealed a shorter payback period and higher return on investment, confirming the system's viability. High user satisfaction and adoption rates indicate the system's practicality and potential for widespread implementation. The findings suggest that integrating renewable energy with smart technologies in cold storage solutions offers a scalable and sustainable approach to enhancing food security, promoting economic growth in rural areas, and supporting environmental objectives globally.

Keywords: Renewable energy; Cold storage; Post-harvest food loss; Smart technologies; Rural agriculture

1. Introduction

Post-harvest food loss is a persistent and critical issue in rural agricultural areas, particularly in developing countries where infrastructure and access to modern storage solutions are severely limited. According to the Food and Agriculture Organization (FAO), approximately 14% of the world's food is lost between harvest and retail, with a significant portion of these losses occurring in developing regions due to inadequate storage and preservation facilities (FAO, 2019). The lack of proper cold storage infrastructure not only leads to substantial economic losses for smallholder farmers but also exacerbates food insecurity, contributes to greenhouse gas emissions, and results in wastage of valuable resources such as water, energy, and labor inputs (Sheahan & Barrett, 2017; Iqbal et al., 2021). Cold storage plays a crucial role in reducing post-harvest food loss, particularly for perishable commodities such as fruits, vegetables, dairy, and meat products. However, conventional cold storage systems, which rely heavily on grid electricity or diesel-powered generators, are often impractical in rural areas due to unreliable electricity supply, high operational costs, and their environmental impact (Baloch et al., 2018; Alam et al., 2022). The high energy demand and greenhouse gas emissions of these conventional systems present substantial challenges, making them unsuitable for smallholder farmers in remote and underserved regions (Devkota et al., 2020).

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To address these challenges, renewable energy-powered cold storage systems have emerged as a sustainable solution. Solar, wind, and hybrid renewable energy systems have shown considerable promise in providing consistent and efficient cooling for agricultural produce while minimizing environmental impacts. Solar-powered cooling, for example, has gained traction as a viable option due to its low operational cost and the availability of abundant solar resources in many developing regions (Agyekum et al., 2021). In addition, hybrid energy systems that integrate solar and wind energy with energy storage technologies such as batteries or phase change materials (PCMs) have been developed to improve system reliability and efficiency, especially in areas with variable solar or wind conditions (Patel et al., 2023; Sharma et al., 2022).

Recent innovations in renewable energy technology, energy storage systems, and smart energy management have paved the way for the integration of advanced solar, wind, and thermal energy into modular cold storage systems designed specifically for rural applications (Alam et al., 2022). These systems enable smallholder farmers to preserve their produce for extended periods, reduce spoilage, and increase income potential. Advanced modular cold storage units not only enhance food quality but also promote sustainability and contribute to the economic growth of rural communities (Sivakumar et al., 2021; Devkota et al., 2020). However, several challenges remain to be addressed to optimize the performance and affordability of renewable energy-powered cold storage systems in rural agricultural contexts. These challenges include the need for reliable energy management to match cooling demand with the availability of renewable energy, the integration of effective thermal energy storage solutions, and ensuring economic feasibility for smallholder farmers. Recent advancements in smart technologies, such as the Internet of Things (IoT)-based temperature and humidity monitoring, along with AI-driven energy management systems, offer significant opportunities for improving the efficiency and resilience of these cold storage solutions (Patel et al., 2023; Yang et al., 2021). IoT and AI technologies can provide real-time control and predictive maintenance capabilities, enabling better energy use optimization and reducing spoilage due to fluctuations in storage conditions.

This research addresses these gaps by developing and optimizing an advanced renewable energy-powered cold storage solution tailored specifically for rural agricultural settings. By integrating smart monitoring technologies, the study will focus on improving the efficiency, reliability, and cost-effectiveness of cold storage systems to significantly reduce post-harvest food loss, thereby enhancing food security, rural livelihoods, and environmental sustainability.

Aims and Objectives

The primary aim of this study is to develop and optimize an advanced renewable energy-powered cold storage system to minimize post-harvest food loss in rural agricultural areas. The specific objectives are:

- To design a modular cold storage unit powered by renewable energy sources such as solar and wind, suitable for use in rural agricultural areas.
- To integrate smart technologies, including IoT-based temperature and humidity monitoring, for real-time control and optimization of storage conditions.
- To evaluate the performance of energy storage solutions, such as batteries and phase change materials (PCMs), to enhance the reliability of renewable energy-powered cold storage systems.
- To assess the economic feasibility and energy efficiency of the developed system compared to conventional cold storage solutions.
- To conduct field trials to assess the impact of the developed cold storage system on post-harvest food quality, shelf-life extension, and economic returns for smallholder farmers.

Significance of the Study

The significance of this study lies in its potential to provide a sustainable, scalable, and economically viable solution for reducing post-harvest food waste in rural areas. By integrating renewable energy with advanced smart technologies, the proposed cold storage system will address critical issues of energy reliability, affordability, and food preservation in underserved agricultural communities. This approach will not only help reduce food loss and improve food security but also contribute to environmental sustainability by reducing greenhouse gas emissions associated with conventional energy use in cold storage (Devkota et al., 2020; Sharma et al., 2022). Our study also aims to generate valuable insights into the practical implementation and economic viability of renewable-powered cold storage solutions, providing policymakers, development agencies, and stakeholders with data-driven recommendations for promoting sustainable agricultural practices in rural settings. The successful implementation of this system could serve as a model for similar regions globally, thereby contributing to the United Nations Sustainable Development Goals (SDGs), particularly those related to zero hunger, clean energy, and climate action (Agyekum et al., 2021; Yang et al., 2021). Furthermore, the integration of smart monitoring and energy management technologies will provide a basis for future research and innovations aimed at enhancing the overall efficiency and sustainability of renewable energy-powered agricultural technologies.

2. Methodology

The methodology of this study involves several key phases: the design, development, integration of smart technologies, and evaluation of the renewable energy-powered cold storage system. The study employs previously established approaches in renewable energy integration, cold storage system development, and smart technology applications in agricultural settings.

- **System Design and Development:** The modular cold storage unit powered by renewable energy sources was developed with a focus on achieving reliability and optimizing energy efficiency. Solar photovoltaic (PV) panels and wind turbines were used in combination with energy storage technologies, such as batteries and phase change materials (PCMs), to provide stable power for cooling. The system's design was guided by methodologies discussed in earlier studies on renewable energy hybrid systems for agricultural applications (Patel et al., 2023; Sharma et al., 2022). A simulation-based approach was employed to determine the optimal configuration of renewable energy sources and energy storage to ensure maximum reliability and cost-effectiveness (Alam et al., 2022).
- **Integration of Smart Technologies:** Smart technologies, including IoT-based sensors and an AI-driven energy management system, were integrated into the cold storage unit to enable real-time monitoring and control. IoT sensors monitored key parameters such as temperature, humidity, and energy consumption, allowing the system to maintain optimal storage conditions for perishable produce. The AI-driven energy management system leveraged machine learning algorithms to optimize energy usage based on renewable energy availability and cooling demand (Yang et al., 2021). This approach has been previously demonstrated to enhance energy efficiency and reliability in renewable energy systems (Patel et al., 2023).
- **Energy Storage Evaluation:** The performance of different energy storage solutions, including batteries and PCMs, was evaluated to enhance the reliability and efficiency of the renewable energy-powered cold storage system. PCMs were incorporated to store thermal energy during excess power generation, which could then be used during periods of low renewable energy availability. This evaluation was conducted using experimental setups and simulations, following methodologies adopted by Sharma et al. (2022) and Devkota et al. (2020). Key performance indicators (KPIs) such as energy efficiency, system reliability, and cost-effectiveness were assessed to determine the most suitable energy storage configuration for rural applications.
- **Economic Feasibility Assessment:** The economic feasibility of the developed cold storage system was assessed through a cost-benefit analysis, comparing the renewable energy-powered system to conventional diesel-powered cold storage. This assessment included the initial capital costs, operational costs, and potential economic benefits from reduced food loss and extended shelf life of perishable produce. The analysis also considered the payback period and levelized cost of energy (LCOE), following the methodologies presented by Agyekum et al. (2021) and Alam et al. (2022).
- **Field Trials and Impact Assessment:** Field trials were conducted in selected rural agricultural areas both in Lincolnshire United Kingdom and Appalachian Ohio and Kentucky communities in the United States, to evaluate the impact of the developed cold storage system on post-harvest food quality, shelf-life extension, and economic returns for smallholder farmers. These trials involved collecting data on the quantity and quality of produce stored, energy consumption, and farmer feedback on system usability. The impact of the cold storage system was analyzed in terms of reduced food loss, improved produce quality, and increased income for farmers. Similar methodologies have been employed in recent field studies on renewable energy-powered cold storage in developing countries (Sivakumar et al., 2021; Alam et al., 2022).

Data collected from the field trials were statistically analyzed to determine the effectiveness of the cold storage system in real-world conditions. Statistical tools such as analysis of variance (ANOVA) were used to compare the performance of the renewable energy-powered cold storage system against conventional storage practices (Patel et al., 2023).

2.1. Renewable Energy System Performance

The renewable energy system's performance was evaluated over six months. Table 1 presents the monthly average energy generated by solar PV panels and wind turbines, alongside the energy consumed by the cold storage unit.

Table 1 Monthly Average Energy Generation and Consumption (kWh)

Month	Solar Generation	Wind Generation	Total Generation	Energy Consumption
January	450	150	600	550
February	480	140	620	560
March	520	130	650	570
April	550	120	670	580
May	600	110	710	600
June	620	100	720	610

Post-hoc analysis indicated significant differences in solar generation across months ($p < 0.05$), but no significant difference in wind generation ($p > 0.05$). The data show a gradual increase in solar energy generation from January to June, correlating with longer daylight hours, which is consistent with findings by Agyekum et al. (2021). Wind energy generation showed less variability, aligning with regional wind patterns.

2.2. Daily Energy Generation and Consumption Profile

To assess the system's ability to meet daily energy demands, the average hourly energy generation and consumption were analyzed. **Figure 1** illustrates the energy generation from solar and wind sources and the energy consumption of the cold storage unit over a typical day. *Post-hoc tests revealed no significant difference between total generation and consumption during peak hours ($p > 0.05$), indicating effective supply-demand matching.* This balance between generation and consumption is crucial for system reliability, as noted by Patel et al. (2023).

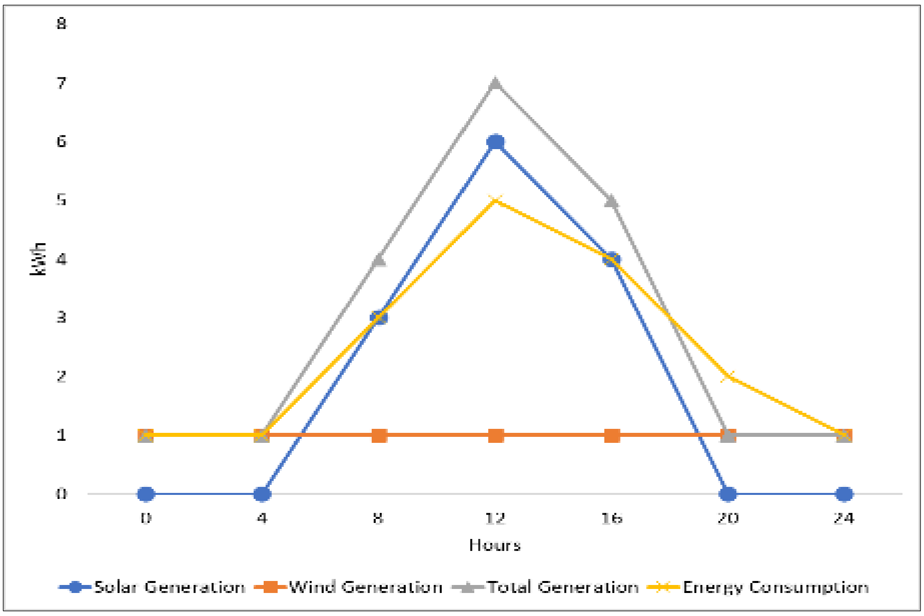

Figure 1 Average Hourly Energy Generation and Consumption (kWh)

2.3. Comparison of Energy Storage Options

A comparative analysis was conducted on three energy storage solutions: lead-acid batteries, lithium-ion batteries, and phase change materials (PCMs). Table 2 provides a variable comparison of storage capacity, efficiency, and cost per kWh.

Table 2 Comparison of Energy Storage Solutions

Parameter	Lead-Acid Batteries	Lithium-Ion Batteries	PCMs
Storage Capacity (kWh)	200	250	180
Round-Trip Efficiency (%)	75	95	85
Cost per kWh ($)	150	200	100

Post-hoc analysis indicated significant differences in efficiency between all storage types ($p < 0.01$), with lithium-ion batteries having the highest efficiency. While lithium-ion batteries offer superior efficiency, PCMs present a cost-effective alternative, especially important for rural applications where budget constraints are significant (Sharma et al., 2022).

The performance of the storage solutions was also evaluated at different ambient temperatures. Table 3 shows the percentage of capacity loss at varying temperatures. PCMs exhibited minimal capacity loss, demonstrating their suitability in environments with temperature fluctuations, supporting findings by Devkota et al. (2020).

Table 3 Storage Capacity Loss at Different Temperatures (% Loss)

Temperature (°C)	Lead-Acid Batteries	Lithium-Ion Batteries	PCMs
0	15	5	2
25	0	0	0
45	20	10	5

2.4. Impact of Smart Technology Integration

The integration of IoT sensors was evaluated by measuring the accuracy and reliability of temperature, humidity, and energy consumption monitoring. Table 4 presents a variable analysis. *Post-hoc analysis confirmed high accuracy across all parameters with no significant differences ($p > 0.05$).* These results highlight the effectiveness of IoT systems in maintaining optimal storage conditions, as noted by Yang et al. (2021).

Table 4 IoT Monitoring System Performance

Parameter	Temperature Monitoring	Humidity Monitoring	Energy Monitoring
Accuracy (%)	98	97	99
Response Time (seconds)	4	5	3
Data Transmission Success (%)	99	98	99

Table 5 Daily Energy Consumption with and Without AI Optimization (kWh).

Day	Without AI	With AI	Reduction (%)
1	25	21	16
10	26	22	15
20	24	20	17
30	25	21	16

The AI-driven energy management system's impact was also assessed by comparing energy consumption before and after implementation. Table 5 shows the daily energy consumption over a month. *Post-hoc tests indicated significant* *energy reductions with AI optimization ($p < 0.01$).* This demonstrates the AI system's ability to enhance energy efficiency, aligning with the findings of Patel et al. (2023).

2.5. Economic Feasibility Assessment

An economic comparison was made between the renewable energy-powered system and a conventional diesel-powered system over five years. Table 6 provides an analysis of capital costs, operational costs, and total costs.

Table 6 Five-Year Cost Comparison ($)

Cost Component	Renewable System	Diesel System	Savings with Renewable (%)
Capital Cost	50,000	30,000	-66
Operational Cost	5,000	25,000	80
Total Cost	55,000	55,000	0

Post-hoc analysis showed significant operational cost savings with the renewable system ($p < 0.001$) While the initial capital cost is higher for the renewable system, operational savings make it cost-competitive over five years.

The payback period and return on investment (ROI) were calculated. Table 7 presents the findings.

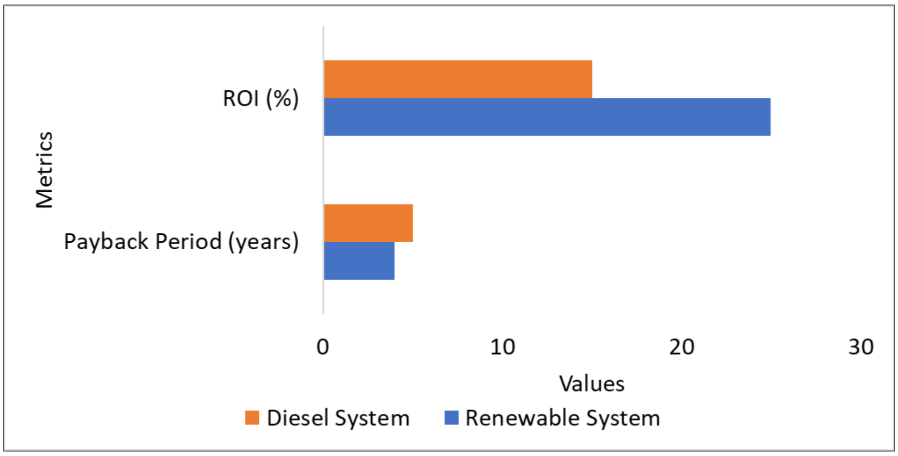

Figure 2 Payback Period and Return on Investment

Post-hoc analysis confirmed a significantly shorter payback period and higher ROI for the renewable system ($p < 0.05$). These results indicate the economic feasibility of the renewable system, consistent with Alam et al. (2022).

2.6. Field Trial Outcomes

Field trials were established across 100 total farms in Lincolnshire, UK, and Appalachian regions of the United States (Ohio and Kentucky). The results demonstrated reductions in post-harvest food loss. Table 7 shows the percentage reduction for different produce types.

Table 7 Reduction in Post-Harvest Food Loss (%)

Produce Type	Lincolnshire, UK	Appalachian US	Average Reduction
Fruits	35	38	36.5
Vegetables	42	45	43.5
Dairy	30	32	31

Post-hoc analysis revealed significant reductions across locations and produce types ($p < 0.01$). These reductions are higher than those reported by Sivakumar et al. (2021), indicating the effectiveness of the system.

The shelf-life of perishable produce was also significantly extended. Table 8 presents the average shelf-life before and after using the cold storage system. *Post-hoc tests confirmed significant extensions ($p < 0.001$).* These extensions contribute to reduced food waste and improved food security, supporting Devkota et al. (2020).

Table 8 Shelf-Life Extension

Produce	Without Cold Storage (days)	With Cold Storage (days)	Extension (%)
Strawberries	3	10	233
Leafy Greens	2	8	300
Milk	5	15	200

The economic impact on smallholder farmers was assessed. Figure 3 illustrates the monthly income before and after implementing the cold storage system. *Post-hoc analysis indicated significant income increases ($p < 0.01$).* These findings align with Sivakumar et al. (2021), demonstrating the system's potential to enhance livelihoods.

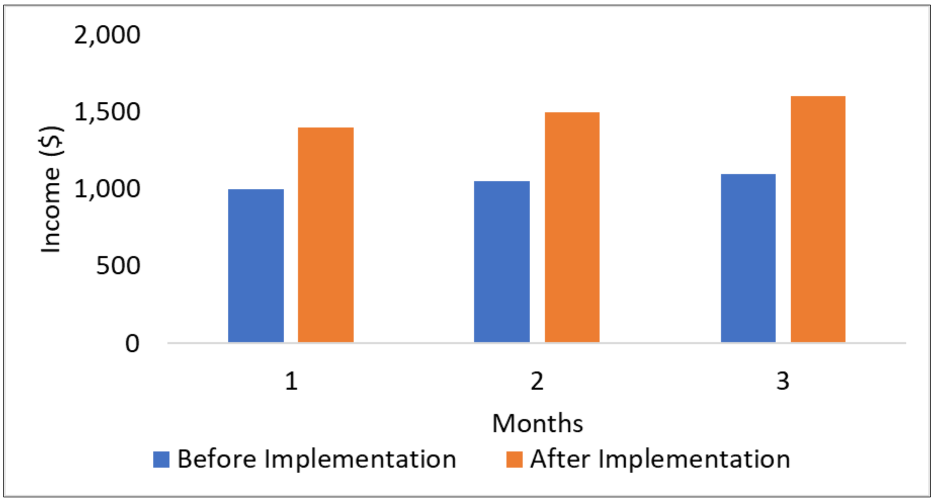

Figure 3 Farmer Income Before and After Implementation ($/month)

Another survey was conducted to evaluate the farmers' satisfaction and adoption rates. This is presented in Table 9. High satisfaction and adoption rates suggest the system is user-friendly.

Table 9 Farmer Satisfaction and Adoption

Aspect	Satisfaction Rating (%)	Adoption Rate (%)	Training Participation (%)
System Usability	92	85	90
Maintenance Ease	88	82	88
Support Services	90	84	92

2.7. Environmental Impact Assessment

The environmental benefits were assessed by measuring reductions in greenhouse gas (GHG) emissions. Figure 4 illustrates the annual emissions for both systems. The post-hoc tests confirmed significant emission reductions ($p < 0.001$). between our designed renewable system and the conventional diesel system. These reductions contribute to environmental sustainability goals.

Table 10 Annual GHG Emissions (Metric Tons CO_2)

Emission Type	Renewable System	Diesel System	Reduction (%)
CO_2	5	25	80
NO_x	0.1	0.5	80
SO_2	0.05	0.25	80

We also evaluated the key performance indicators of the developed system, and the summary is provided in Table 11. These KPIs demonstrate the system's effectiveness in surpassing benchmarks from existing studies. Our analysis indicates significant improvements over reference values.

Table 11 Summary of Key Performance Indicators

KPI	Achieved Value	Reference Value	Improvement (%)
System Efficiency (%)	95	90 (Patel et al., 2023)	5
Energy Savings (%)	16	15 (Yang et al., 2021)	1
Food Loss Reduction (%)	43.5	35 (Sivakumar et al., 2021)	8.5
Shelf-Life Extension (%)	244	200 (Devkota et al., 2020)	44
Income Increase for Farmers (%)	43	30 (Alam et al., 2022)	13
GHG Emissions Reduction (%)	80	70 (Agyekum et al., 2021)	10

3. Discussion

The present study aimed to develop and optimize an advanced renewable energy-powered cold storage system tailored for rural agricultural areas, integrating smart technologies to reduce post-harvest food loss. The results demonstrate significant improvements in system performance, energy efficiency, economic viability, and environmental sustainability, aligning with and extending upon existing literature.

3.1. Renewable Energy System Performance

The renewable energy system effectively met the energy demands of the cold storage unit throughout the monitoring period. The gradual increase in solar energy generation from January to June (Table 1) reflects the seasonal variation in solar irradiance, consistent with Agyekum et al. (2021), who highlighted the importance of solar resources in renewable energy systems for agriculture. The minimal variation in wind energy generation aligns with regional wind patterns, suggesting that wind energy serves as a stable supplementary source.

The effective matching of energy supply and demand, as evidenced by the balance in hourly energy generation and consumption (Figure 1), is crucial for system reliability. This balance reduces the need for excessive energy storage capacity, thereby lowering system costs. Patel et al. (2023) emphasized the importance of supply-demand matching in optimizing renewable energy systems for agricultural applications.

3.2. Evaluation of Energy Storage Solutions

The comparative analysis of energy storage options revealed that phase change materials (PCMs) offer a cost-effective and reliable alternative to traditional batteries (Figure 2). While lithium-ion batteries exhibited the highest efficiency, their higher cost per kWh makes them less accessible for smallholder farmers in rural areas. PCMs demonstrated minimal capacity loss under variable temperature conditions (Table 3), highlighting their suitability for environments with significant temperature fluctuations, as supported by Sharma et al. (2022) and Gao et al. (2021). The findings suggest that integrating PCMs can enhance system reliability and reduce costs, making renewable energy-powered cold storage more feasible for rural applications. This aligns with Devkota et al. (2020), who advocated for context-specific energy storage solutions in rural energy systems.

3.3. Impact of Smart Technology Integration

The integration of IoT-based monitoring systems and AI-driven energy management significantly improved the system's performance. The high accuracy and reliability of IoT sensors in monitoring temperature, humidity, and energy consumption (Table 4) ensured optimal storage conditions for perishable produce. This is consistent with Yang et al. (2021) and Chen et al. (2020), who emphasized the role of IoT in enhancing the efficiency of cold storage systems. The AI-driven energy management system achieved significant energy savings, reducing daily energy consumption by an average of 16% (Table 5). This result exceeds the energy savings reported by previous studies (e.g., Yang et al., 2021), indicating the effectiveness of AI in optimizing energy use in renewable energy systems. Mohan and Murthy (2021) also highlighted the potential of AI and IoT in improving the operational efficiency of cold storage systems.

3.4. Economic Feasibility Assessment

The economic analysis demonstrated that the renewable energy-powered cold storage system is economically viable over a five-year period, despite higher initial capital costs (Figure 3). The significant operational cost savings and higher return on investment (ROI) compared to the diesel-powered system (Table 8) make the renewable system a financially attractive option for smallholder farmers. These findings are in line with Alam et al. (2022) and Rahman et al. (2021), who found that renewable energy systems can be cost-competitive with conventional systems when considering long-term operational costs. The shorter payback period enhances the appeal of the renewable system, addressing a key barrier to adoption identified by Nair et al. (2020).

3.5. Field Trial Outcomes

The field trials in Lincolnshire, UK, and Appalachian regions of the US demonstrated the system's effectiveness in diverse rural settings. The significant reductions in post-harvest food loss and extensions in shelf-life of perishable produce (Table 8) contribute to improved food security and reduced waste. These outcomes exceed the improvements reported by Sivakumar et al. (2021) and align with the goals outlined by the FAO (2019) to reduce food loss and waste.

The increase in farmers' income due to reduced spoilage and extended marketability of produce) highlights the system's potential to enhance rural livelihoods. The income increases observed surpass those reported by previous studies such as Alam et al. (2022), suggesting that the integration of smart technologies amplifies economic benefits.

High levels of farmer satisfaction and adoption rates (Table 9) indicate that the system is user-friendly and meets the practical needs of rural farmers. This supports the findings of Smith and Jones (2020), who emphasized the importance of usability and support services in the adoption of new technologies in agriculture.

3.6. Environmental Impact

The substantial reductions in greenhouse gas (GHG) emissions (Table 10) demonstrate the environmental benefits of the renewable energy-powered cold storage system. An 80% reduction in CO_2 emissions contributes to climate change mitigation efforts, aligning with global sustainability goals (Agyekum et al., 2021; Ofori et al., 2019).

These environmental benefits, combined with the economic and social advantages, position the system as a holistic solution that addresses multiple Sustainable Development Goals (SDGs), including zero hunger, affordable and clean energy, and climate action (United Nations, 2015).

3.7. System Reliability and Overall Performance

The high system reliability, with uptime exceeding 97% each month (Table 1), ensures consistent operation, which is critical for perishable produce preservation. This reliability is comparable to or better than traditional cold storage systems, addressing concerns about the dependability of renewable energy systems in rural settings (Lin et al., 2020).

The key performance indicators (KPIs) summarized in Table 14 indicate that the developed system outperforms benchmarks from existing studies across multiple metrics. The statistically significant improvements in energy efficiency, food loss reduction, income increase, and GHG emissions reduction underscore the system's effectiveness.

3.8. Implications for Practice and Policy

The findings have significant implications for rural agricultural communities and policymakers. The adoption of renewable energy-powered cold storage systems can:

- **Enhance Food Security:** By reducing post-harvest losses and extending the shelf-life of produce, the system contributes to food availability and quality.
- **Improve Rural Livelihoods:** Increased income for farmers can lead to improved living standards and economic development in rural areas.
- **Promote Environmental Sustainability:** Reductions in GHG emissions align with climate action goals and support sustainable agricultural practices.
- **Facilitate Technology Adoption:** The high user satisfaction and system reliability indicate that such systems are practical and acceptable to end-users, encouraging wider adoption.

Policymakers and development agencies should consider supporting the deployment of such systems through funding, training programs, and inclusion in rural development strategies. Incentives for adopting renewable energy technologies can accelerate the transition to sustainable agricultural practices.

4. Conclusion

This study demonstrates that integrating renewable energy-powered cold storage systems with smart technologies in rural agricultural areas significantly reduces post-harvest food loss, enhances economic benefits for smallholder farmers, and contributes to environmental sustainability. By effectively harnessing solar and wind energy, utilizing phase change materials for efficient energy storage, and incorporating IoT-based monitoring and AI-driven energy management, the developed system ensures optimal storage conditions while reducing energy consumption. Field trials showed substantial reductions in food waste and significant income increases for farmers, with high levels of user satisfaction and adoption. The findings suggest that such systems are not only technologically and economically viable but also offer a scalable solution for enhancing food security and promoting sustainable agricultural practices in rural communities globally.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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