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(Review Article)

Renewable energy integration in agricultural value chains: An assessment of economic and operational benefits

Norhanah M. Barodi [1, *], Aldrees Ansary B. Guro [2] and Norhanie D. H.Jamel [3]

[1] *Department of Plant Science, College of Agriculture, Mindanao State University, Marawi City, Philippines.*
[2] *Department of Agribusiness Management, College of Agriculture, Mindanao State University, Marawi City, Philippines.*
[3] *Department of Agricultural Education and Extension, College of Agriculture, Mindanao State University, Marawi City, Philippines.*

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Abstract

This review synthesizes evidence on economic and operational benefits of renewable energy integration across agricultural value chains, addressing gaps in comprehensive value-chain assessments beyond isolated farm-level analyses. A systematic literature review was conducted following PRISMA guidelines using Scopus, Web of Science, and Google Scholar. Peer-reviewed articles and institutional reports published between 2006 and 2026 were analyzed thematically. Inclusion criteria required studies reporting quantitative economic or operational metrics of renewable energy applications in agriculture. Out of 312 potentially relevant records, 41 studies met the inclusion criteria after screening. Data extraction captured technology types, value chain nodes, economic outcomes, and operational outcomes. Results showed that solar-powered irrigation reduces operational energy costs compared to diesel alternatives, though economic viability depends heavily on local fuel prices, subsidy regimes, and access to financing. Agrivoltaic systems generate dual revenue streams but exhibit trade-offs between energy production and agricultural productivity that vary by crop species and climate conditions. Biomass energy integration from agricultural residues contributes to circular economy goals, yet feedstock seasonality and transportation costs constrain economic viability. Solar cold storage reduces post-harvest losses, but high initial capital costs remain prohibitive for smallholder farmers. Smart irrigation improves water use efficiency, though groundwater over-abstraction risks emerge when energy costs decline. Overall, renewable energy integration delivers substantial yet context-dependent economic and operational benefits across agricultural value chains. Realization requires addressing financing barriers, technical capacity gaps, and institutional support deficits. Future research should prioritize longitudinal assessments, standardized economic frameworks, and integrated value chain modeling.

Keywords: Agricultural Value Chains; Economic Benefits; Operational Efficiency; Renewable Energy; Sustainable Agriculture

1. Introduction

The global agricultural sector stands at a critical point between two competing demands: ensuring food security and reducing greenhouse gas emissions (Aziz et al. 2024). This situation has led to increased research focus and policy development efforts examining how renewable energy should be implemented to create carbon-free agricultural systems that also generate financial benefits. The agricultural value chain encompasses the full spectrum of activities from pre-production inputs to on-farm operations, post-harvest processing, storage, and distribution to each node which presents different energy needs that can be met through renewable energy sources (Martinho, 2018). The

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[*] Corresponding author: Norhanah M. Barodi

agricultural sector needs to adopt renewable energy systems since traditional fossil fuel energy systems now face rising expenses, unpredictable supply issues and new environmental regulations (Bathaei & Štreimikienė, 2023).

The economic rationale for renewable energy integration in agriculture needs to be evaluated since it provides more than basic cost replacement through its advantages of increased productivity and decreased business risks and its ability to produce benefits throughout the entire value chain system. Recent studies show that renewable energy systems can boost energy-demanding agricultural operations beyond existing productivity levels, especially in Sub-Saharan Africa which currently relies on biomass and diesel as its main energy sources (Algarni et al., 2023). The productivity increases occur through three different channels which include lower energy prices, improved operational efficiency and value chain spillover benefits, including processing and cold chain logistics. The reduction in solar photovoltaic (PV) system levelized costs which has exceeded 80% since 2010 makes solar-powered agricultural systems financially viable compared to traditional methods in all agricultural regions (Abdelhamid et al., 2025). The economic value depends on context as the finanacial feasibility of renewable energy adoption is influenced by fossil fuel subsidy systems, labor costs, and access to financing (Hartung & Pluschke, 2018).

The agricultural value chains of solar energy applications experience their most transformative impact through their multiple implementations which include irrigation systems, drying technologies, cold storage facilities, greenhouse climate control systems, and on-farm electricity production. The agricultural industry has widely adopted solar-powered irrigation systems (SPIS) since they deliver significant economic benefits to areas which depend on diesel pump irrigation for their operational expenses. The research conducted by Hussain et al. (2023) shows that SPIS technology helps farmers in two ways by reducing their irrigation energy costs and removing their need for fuel supply chains which make them vulnerable to price changes and disruptions. The research conducted by Durga et al. (2024) shows that solar-powered irrigation systems have become expensive for Sub-Saharan Africa since their market development remains insufficient and geographical limitations exist. Farmers face challenges in adopting these systems since they need protection against unsafe situations, there are no available financial incentives and their operational abilities are insufficient. The application of solar energy in protected agriculture extends beyond irrigation to drive greenhouse systems which create heating, ventilation and functional lighting that enables extended crop development periods while producing higher quality crops and providing better market opportunities for premium horticultural goods (Espitia et al. 2024). The bibliometric analysis conducted by Espitia et al. (2024) shows that academic research about solar-greenhouse integration has increased at an exponential rate since scientists now understand its economic benefits and technological development has reached its current state, but the study also identifies ongoing issues with system optimization and design needs that depend on different climatic conditions.

Researchers have dedicated significant efforts to study agrivoltaic systems which combine solar photovoltaic systems with ongoing agricultural operations as a method to optimize land use while achieving both energy and food production targets. The global agrivoltaics sector has expanded rapidly in recent years alongside continued growth in worldwide solar photovoltaic deployment, reflecting increasing commercial and research interest in integrated food and energy production systems (Widmer et al., 2024; IEA PVPS, 2026). Agrivoltaic systems enable farmers to receive two different revenue streams from their operations according to economic assessments which show that farmers earn additional income through solar lease payments while their agricultural activities continue (Singla et al., 2025). Chalgynbayeva et al. (2023) conducted a comprehensive bibliometric review of global agrivoltaic research trends which showed that scholars increasingly study the effects of crop yield relationships, water use efficiency, and economic optimization models. Agrivoltaic systems produce essential trade-offs according to research since they decrease photosynthesis and crop yields through specific configurations which mainly affect shade-intolerant plant species while they decrease both evapotranspiration and irrigation water needs (Weselek et al., 2019; Sirnik et al., 2023). Agrivoltaic systems show different economic results since their financial performance depends on three main factor; crop types, weather patterns, and system configuration specifications.

Biomass energy derived from agricultural residues represents an important renewable energy source that provides environmental benefits and drives economic advantages throughout the agricultural value chain while supporting circular economy practices. The global biomass supply will experience significant growth since agricultural residues will serve as a major feedstock source for bioenergy production (Perea-Moreno et al., 2019). Agricultural biomass valorization through the circular economy framework enables waste transformation into resources that allows conversion of rice straw, wheat straw, corn stover and palm kernel shells into bioenergy, biofertilizers and biochemicals (Tun et al., 2019). The research conducted by Janiszewska and Ossowska (2022) reveals that agricultural biomass serves as a crucial renewable energy resource for European Union countries since policy frameworks have incentivized the conversion of agricultural residues into energy. Biomass energy systems face economic challenges since their feedstock availability depends on seasonal patterns. Transportation costs increases due to dispersed locations. Preprocessing requirements also vary by region and scale depending on the geographical area and operational size

(Tshikovhi et al., 2025). Advanced biofuels produced from agricultural residues achieve high energy return on investment ratios yet supply chain development and operational scale economies must work together for organizations to achieve their desired advantages.

The energy requirements of post-harvest processing and storage facilities in agricultural value chains reach their peak since these operations benefit from renewable energy sources that provide substantial improvements in both operational efficiency and financial performance. Developing regions face agricultural post-harvest losses which reach 30 to 40 percent since they lack sufficient cold chain infrastructure to store their goods (Amjad et al., 2023). Solar-powered cooling systems provide remote agricultural communities with sustainable cold storage solutions which do not depend on grid electricity or diesel generators. Ukoba et al. (2018) showed that solar energy solutions can help African regions which lack effective cold chain systems to reduce their post-harvest losses for roots and tubers. The techno-economic assessment performed by Barzigar et al. (2025) demonstrates that solar-assisted drying systems with built-in thermal storage capabilities enable facilities to decrease their drying costs while enhancing product quality and extending product shelf life. The research conducted by Tripathy et al. (2025) found that smallholder farmers face challenges adopting storage solutions since the solutions require both high capital costs and advanced technical features and they depend on specialized support systems.

The renewable energy sector shows strong economic and operational advantages through its various applications yet research needs to investigate complete value-chain assessments that measure operational connections between different system elements and their total impacts. Existing literature has predominantly examined renewable energy applications in isolation—focusing on irrigation, drying, or storage as discrete activities—rather than analyzing integrated value-chain configurations where renewable energy substitution at multiple nodes generates compounding benefits (Pietrzak et al., 2025). The different economic assessment methods used in research studies create challenges for researchers who want to study results from various studies and make unified conclusions through meta-analysis. Research on renewable energy integration has focused on farm-level techno-economic feasibility studies yet no studies exist which show how renewable energy adoption impacts all value chain entities from processors to retailers (Kumar et al., 2024).

The study of renewable energy implementation in agriculture value chains remains underexplored due to lack of measurement of the total economic effects of renewable energy integration across agricultural value chains including direct, indirect, multiplier, and long-term effects. The research will review existing evidence about economic and operational advantages of renewable energy systems while determining essential research areas that prevent proper implementation of renewable energy solutions in agricultural environments. The research aims to examine benefits of renewable energy systems throughout agricultural value chain operations while assessing economic benefits and operational efficiency results from current research studies and determining essential research fields and policy development areas that will help agricultural sector transition to sustainable energy solutions.

2. Methodology

2.1. Research Design

The research used a systematic literature review method to combine scientific evidence about renewable energy integration into agricultural value chains. The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure methodological rigor, transparency, and reproducibility. A comprehensive search strategy was developed to obtain peer-reviewed journal articles and institutional reports which were published between 2006 and 2026.

2.2. Population, Sample, and Sampling

The target population comprised all published scholarly works examining renewable energy applications in agricultural contexts with explicit economic or operational outcome reporting. The study used Scopus, Web of Science, and Google Scholar as its primary academic database sources. The search strings included renewable energy terms (solar, wind, biomass, and biogas) and agricultural application terms (irrigation drying, cold storage, greenhouse systems, and agrivoltaics) and economic outcome terms (cost-benefit return on investment operational efficiency productivity).

Inclusion criteria required studies to: (1) report quantitative economic or operational metrics; (2) focus on agricultural value chain applications; (3) be published in English; and (4) provide sufficient methodological detail for quality assessment. Exclusion criteria eliminated: (1) non-agricultural renewable energy applications; (2) purely theoretical or modeling studies without empirical validation; (3) conference abstracts or non-peer-reviewed sources lacking sufficient detail; and (4) publications predating 2015. The initial database search yielded 312 potentially relevant records, which were screened at the title/abstract level, resulting in 89 potentially relevant articles. Full-text review further excluded 49 articles that failed to meet inclusion criteria, yielding a final sample of 41 studies for qualitative synthesis. The selection process was documented following PRISMA protocols.

2.3. Data Extraction and Analysis

A standardized data extraction form was used to record study characteristics, including author information, study year, study location, research design, and details about renewable energy technology, agricultural value chain elements and economic results which included cost reduction, revenue enhancement, payback period, net present value, and operational results which included efficiency improvements, yield changes, loss reduction, and all elements of the study's quality assessment. The researchers used thematic analysis to organize their results according to value chain nodes and different technology types. The researchers converted economic metrics into 2024 USD values to enable temporal comparison analysis, using 2024 as the most recent complete reference year with consistently available inflation adjustment indices and economic datasets during the review process. The quality assessment process started with peer-reviewed journal articles as the main focus while credible institutional reports from authoritative sources like FAO served as supplementary material when peer-reviewed evidence proved insufficient.

3. Results and Discussion

3.1. Solar-Powered Irrigation: Costs, Viability, and Water Risks

The solar-powered irrigation systems (SPIS) function as the most researched renewable energy technology which agricultural value chains employ but their economic and operational advantages display variable evidence across different geographical regions and various farm sizes. The economic analysis by Biberci (2023) demonstrates that solar-powered agricultural irrigation systems achieve favorable payback periods depending on local solar insolation, diesel price differentials, and crop value, with lifetime cost savings exceeding conventional diesel-powered alternatives. The findings of this study correspond with the techno-economic assessment which Kelley et al. (2010) performed to demonstrate solar-powered irrigation systems' viability through their complete lifecycle cost analysis that showed solar PV pumping systems cut down operational energy costs throughout their 20-year operational period. The research conducted by Al-Dalaeen (2024) established that solar energy systems present economic benefits compared to other renewable energy sources yet their operational cost benefits change based on the agricultural tasks and weather patterns of different farming methods.

The economic viability of SPIS depends on its context which becomes evident through different regional comparisons. The researchers Hartung and Pluschke (2018) documented that countries make different payback period calculations which show that Senegalian solar pumps deliver quick payback to horticulture operations while Bangladeshi systems require extended payback times which make them unattractive to private investors despite their lower operational expenses than diesel. In India SPIS operate as economically viable systems only under current subsidy conditions when their annual usage exceeds the infrequent thresholds which results in their inability to compete against subsidized grid power according to Hartung and Pluschke (2018). The different results demonstrate that economic viability depends on technology performance but also on institutional settings, subsidy systems and market frameworks which affect cost comparisons. Chaudhari (2024) emphasizes that solar-powered irrigation systems provide small-scale farmers with important opportunities to decrease energy expenses and gain operational independence. However, the realization of these benefits depends on the right system size and technical assistance and affordable financing solutions.

The operational advantages of SPIS in developing countries who rely on diesel-powered irrigation systems and face interruptions in their fuel distribution networks extend beyond their ability to decrease expenses since they provide both dependable supply systems and consistent production processes. Hussain et al. (2023) documented that solar irrigation potential in Pakistan remains substantial yet underutilized, with key challenges including high upfront capital costs, limited technical knowledge, and inadequate after-sales service infrastructure. Durga et al. (2024) discovered multiple obstacles which prevent Sub-Saharan Africa from adopting solar irrigation technology since it has uncovered operational hazards, lacks proper incentives and does not possess sufficient implementation capacity. The combined results of different studies show that the primary obstacles which prevent SPIS technology from spreading across various locations arise from institutional shortcomings and capital cost constraints which exist in the existing system.

The SPIS operational efficiency improvements result from multiple systems which provide benefits beyond their ability to cut energy expenses. Smart irrigation systems that use solar power together with soil moisture sensors, weather stations and automatic control systems provide better water management results than standard timer-based irrigation methods and manual irrigation systems (Abdelhamid et al., 2025). Hartung and Pluschke (2018) explain that SPIS systems require proper management and regulation since their low energy costs lead to two problems. This creates a trade-off, as the two systems can work against each other. The review by Hahn et al. (2025) on farmers' perspectives regarding agriculture's role in sustainable energy systems shows that farmers understand the economic advantages but their adoption decisions depend on their assessment of water resource sustainability and existing regulatory frameworks.

3.2. Agrivoltaic Systems: Dual Benefits and Crop Trade-offs

Agrivoltaic systems create an innovative method for renewable energy integration which proves that energy generation and food production do not need to compete for land use. The bibliometric review by Chalgynbayeva et al. (2023) identified rapidly accelerating global research trends in agrivoltaics, with particular emphasis on crop yield interactions, water use efficiency, and economic optimization models. The systematic review by Widmer et al. (2024) synthesized evidence from numerous studies, concluding that agrivoltaic systems can increase land productivity compared to sole-use agriculture or solar installations when measured through combined food and energy output. The total agricultural measurement fails to reveal essential differences between specific crops and different climate conditions which affect a farm's economic performance.

Agrivoltaic systems require detailed empirical studies to evaluate their actual advantages and disadvantages. Weselek et al. (2019) reviewed applications, challenges, and opportunities in agrophotovoltaic systems, finding that photovoltaic panel shading can reduce photosynthesis and crop yields for shade-intolerant species while simultaneously reducing evapotranspiration and irrigation water requirements. The study conducted by Sirnik et al. (2023) assessed circularity, landscape experience aspects of agrivoltaics and discovered that panel shading reduces irrigation water needs through its effects on microclimatic conditions although different crop types show different yield responses. Soto-Gómez (2024) examined various crop, livestock and solar panel integration methods. He discovered that agrivoltaic systems enhance soil moisture retention while decreasing plant and animal heat stress, creating microclimates that boost crop growth for extended periods. The advantages of these systems depend on specific crops since lettuce, tomato and certain forage crops thrive under partial shade but cereal crops and other shade-intolerant species face yield declines which make agricultural production unprofitable unless energy revenues fully offset their losses.

The trade-offs produce significant effects on policy requirements. Buzzelli (2024) analyzed when agrivoltaics are profitable compared to agriculture and photovoltaics, finding that economic viability depends on the relative prices of agricultural products and electricity, system configuration, and policy incentives. The analysis indicates that market forces will convert agricultural land into solar power facilities unless policy interventions create protection for the food-energy-economic nexus. Singla et al. (2025) emphasized that agrovoltaic applications for sustainable agriculture require context-specific design approaches, as crop yield responses to shading vary substantially across species and environmental conditions. The findings demonstrate that agrivoltaic systems need specially developed policy frameworks to achieve their economic potential since these systems must balance private financial gains with public needs for food security and land conservation.

3.3. Biomass Energy: Circular Value and Scale Constraints

The agricultural value chains of biomass energy systems demonstrate circular economy applications which face economic challenges since their feedstock logistics needs and operational size requirements differ across different operational environments. Modern bioenergy provides essential feedstock from agricultural waste materials and biomass which serve as major components of worldwide primary energy supply according to Perea-Moreno et al. (2019). The research by Perea-Moreno et al. (2019) analyzed global research patterns that study biomass as a renewable energy source, showing increased academic and governmental focus on using agricultural waste materials for sustainable development methods.

Multiple pathways exist through which biomass energy integration delivers economic advantages to agricultural value chains but these pathways face significant restrictions. Janiszewska and Ossowska (2022) examined the role of agricultural biomass as a renewable energy source in European Union countries, finding that biomass energy policies have created new revenue streams for farmers while contributing to rural economic development. Agricultural residue biomass energy in Southeast Asia shows considerable potential according to Tun et al. (2019) but its economic viability suffers from obstacles that affect collection, storage and preprocessing operations. The circular economy framework demonstrates that centralized processing systems for agricultural waste valorization will increase farmer incomes but Tshikovhi et al. (2025) show that biomass energy systems face economic challenges because of their dependency on feedstock availability, transportation expenses and preprocessing needs.

Biomass energy systems in agricultural value chains provide operational benefits through three main advantages such as improved energy security, reduced waste management costs and increased soil fertility through biochar and digestate application methods. The review by Lim et al. (2012) on biomass utilization from the rice industry documented that rice husk combustion for power generation reduces waste disposal volumes while generating process heat for parboiling and drying operations. The researchers Liu et al. (2014) studied how renewable energy production from agricultural biomass would impact Canada while discovering that biomass energy systems help farmers cut greenhouse gas emissions and provide job opportunities for residents in rural areas. The research by Al-Dalaeen (2024) found that bioenergy systems research shows higher operational costs than solar energy systems when used in agricultural settings thus making solar power more cost-effective when solar resources are sufficient.

The economic analysis of biomass energy systems faces a major restriction since biomass energy systems depend on their operational scale. Mohammed et al. (2013) conducted a study about agricultural biomass as a source for decentralized rural energy systems in Ghana and found that although the theoretical potential reached high levels, the economic feasibility needed minimum production levels which would exceed what smallholder communities could achieve. Saleem (2022) explained that agricultural biomass produces renewable sustainable energy sources which can bring economic advantages only when supply chains develop properly through establishment of optimal production capacities and implementation of government funding programs. The results of these studies show that the advantages of biomass energy systems depend on specific environmental conditions which need both institutional backing and adequate operational capacity to reach their maximum potential.

3.4. Solar Cold Storage: Loss Reduction and Capital Barriers

The agricultural value chains face their most significant challenge in developing regions since they lack dependable cold storage systems for handling perishable goods. Renewable energy-powered cold storage systems offer decentralized solutions that address this challenge while reducing operational energy costs, though high capital requirements remain a significant barrier. Hussain et al. (2025) developed and evaluated a solar-powered cold storage system for perishable agricultural products, which showed that solar photovoltaic-driven vapor compression cooling technology can maintain 4–8°C temperatures with low electricity needs, which results in longer product shelf life than storage at room temperature. The operational enhancements lead to decreased post-harvest waste that occurs with fruits and vegetables.

The economic advantages of solar cold storage operations extend their benefits through two main channels which enable farmers to reach new markets while achieving better market prices. The researchers Amjad et al. (2023) studied decentralized solar-powered cooling systems which provide fresh produce storage in developing regions and demonstrated that cold storage facilities let farmers keep their products during excessive market supply to sell them at times of high market value that leads to improved financial results. The researchers Tripathy et al. (2025) conducted a techno-economic assessment which showed that solar-powered cold rooms function as cost-effective storage facilities for fruits and vegetables after demonstrating their economic viability for small and medium-sized businesses under particular circumstances. The capital constraint creates an essential trade-off since the technology becomes economically feasible after installation yet the farmer groups who would benefit most from it cannot access it due to existing barriers.

Solar cold storage systems deliver operational efficiency improvements through three benefits that include decreasing the need for inconsistent grid power and terminating diesel generator expenses and achieving better temperature management results. Ukoba et al. (2018) demonstrated that solar energy applications in post-harvest handling of roots and tubers in Africa can reduce storage losses significantly, while Mehtab et al. (2026) reviewed smart-farm-integrated cold thermal energy storage systems, finding that solar-powered cooling with thermal storage can achieve favorable energy efficiency coefficients. The authors report that solar cold storage systems require advanced technical expertise and financial resources that exceed what smallholder farmers typically possess according to Kumar et al. (2024) since these systems need to function with different renewable energy technologies.

3.5. Renewable Energy in Protected Agriculture

Protected agriculture through greenhouse cultivation operations represents an energy-intensive value chain node that achieves economic and operational advantages through renewable energy integration, but this approach necessitates crucial design decisions and specific climatic system requirements. Espitia et al. (2024) conducted a technical and bibliometric review of solar energy applications in protected agriculture, identifying rapid growth in research attention toward greenhouse-integrated photovoltaic systems, solar thermal collectors, and passive solar design. The review documented that solar greenhouse systems can reduce heating energy requirements while maintaining or improving crop yield and quality, though optimal configurations vary substantially across climatic zones.

Renewable energy integration into greenhouse systems generates economic advantages which extend beyond energy cost reductions to provide longer growing period, better crop quality and improved market access. Espitia et al. (2024) demonstrated that solar greenhouse technologies enable continuous production throughout the year in temperate regions that results in higher yearly output than open-field farming methods. The bibliometric study found ongoing difficulties which included system optimization problems together with climate-specific design needs and the requirement for complete energy-water-crop modeling systems to achieve maximum financial benefits. The research results demonstrate that while the economic potential exists at a significant level the process of achieving it requires advanced technical expertise combined with tailored system solutions which small operators will find difficult to obtain.

The operational efficiency of solar greenhouse systems shows better results through three advancements which include better systems that control temperature, humidity, improved photosynthetic performance that decreases the need for carbon dioxide and integrated irrigation systems that enhance water use efficiency. The study by Abdelhamid et al. (2025) created and tested a solar-powered smart irrigation system for urban agriculture which proved that integrated solar-greenhouse-irrigation systems can achieve substantial water use efficiency improvements while reducing energy costs. The research by Al-Dalaeen (2024) shows that geothermal systems can provide operational cost advantages for certain greenhouse heating applications that proves that organizations should choose renewable energy technologies based on their specific locations instead of automatically selecting solar power systems.

3.6. Wind and Hybrid Systems: Applications and Limitations

The agricultural value chains use solar and biomass technologies as their primary renewable energy sources while wind energy and hybrid systems provide additional advantages in particular situations that are limited by both geographical and economic factors. Barzigar et al. (2025) conducted a review of solar and wind-assisted drying systems for agricultural products that included thermal storage components and discovered that hybrid renewable energy systems deliver significant reductions in drying energy expenses while maintaining product quality through their ability to manage temperature and humidity levels. The hybrid systems which use multiple renewable energy sources together with storage systems provide reliable performance since they solve the intermittency problems that limit the functionality of single renewable energy technologies.

The economic assessment of wind energy in agricultural contexts shows beneficial results for suitable locations but needs to restrict its findings to specific geographic areas. Bolyssov et al. (2019) studied renewable energy solutions for agricultural purposes, which showed that wind turbines installed on farmland create extra income while using only a small part of the land. Agricultural wind energy systems depend on specific areas that possess sufficient wind resources, which restricts their use since solar technologies can function in several different agro-ecological regions. Al-Dalaeen (2024) states that the agricultural sector experiences wind energy operational cost differences based on various contextual elements, which include grid connection status and existing maintenance resources and local wind pattern stability.

3.7. Cross-Technology Comparison: Economic Performance and Metrics

Studies have examined renewable energy advantages which different agricultural value chain stages show to create specific economic benefits and operational effects that make it impossible to define universal operational procedures. Solar-powered irrigation systems generally demonstrate favorable economic metrics since their payback periods remain reasonable while their operational expenses decrease by significant amounts yet these metrics display high variability across different subsidy systems, fuel price conditions and different financing arrangements (Biberci, 2023; Hartung & Pluschke, 2018). Agrivoltaic systems require extended payback times yet they provide distinct benefits through their efficient land utilization since their financial results depend on how crops interact with specific climate conditions that result in yield losses or gains (Weselek et al., 2019; Sirnik et al., 2023). Biomass energy systems exhibit the most variable economics since their successful implementation demands minimum operational scales together with supply chain coordination which smallholder environments find hard to establish (Tun et al., 2019; Mohammed et al., 2013).

The measurement methods used in different studies create difficulties for researchers who want to compare study results. Different studies report outcomes in percentage reductions absolute currency values and payback periods while using net present values and land productivity indices that makes direct comparison between their results impossible. Pietrzak et al. (2025) identified this lack of standardization as a critical research gap which shows how common economic evaluation frameworks need to exist before scientists can conduct meta-analytic synthesis and create evidence-based policies. The different methods used in this research create a situation where individual studies show strong benefits but their results cannot be used to compare different studies or apply findings to other research.

3.8. Limits of Economic Benefits

The literature shows that renewable energy integration into agricultural value chains produces economic and operational advantages in only some situations while wasting financial resources in multiple areas. The researchers Durga et al. (2024) showed that solar irrigation systems which appear to offer benefits in Sub-Saharan Africa face obstacles because of insufficient regulations, weak local institutional funding and restricted market growth. Hartung and Pluschke (2018) showed that private investors find SPIS unattractive as of its long payback periods in Bangladesh while solar solutions become economically unfeasible in India except during periods of high power usage since of subsidized grid electricity. The research results show that institutional and policy frameworks have the ability to eliminate all economic benefits which renewable energy technologies provide.

Agrivoltaic systems create a balancing problem that affects energy generation and farming operations since their advantages might not become realized. Buzzelli (2024) found that converting farmland entirely to traditional photovoltaic panels may generate higher annual revenue than agrivoltaic configurations under certain price scenarios. The research showed that agrivoltaic systems decrease shade-intolerant crops as the technology only works for particular crop-and-climate combinations. The research results demonstrate that agrivoltaics should not become automatically endorsed without proper assessment of their suitability to specific situations.

The benefits of smallholder farming and commercial farming operations show different results since their operational sizes create a crucial difference. Chaudhari (2024) examined solar-powered irrigation systems used by small-scale farmers and discovered that the systems provide substantial energy savings and operational independence but their implementation requires farmers to have access to financial resources and technical education which remains inaccessible for the most disadvantaged agricultural workers. Hartung and Pluschke (2018) discovered that smallholder farmers face financial difficulties as they need to make expensive initial investments which they cannot handle and their agricultural output generates minimal income. The results demonstrate that renewable energy advantages distribute unfairly since they benefit only large-scale operators who have sufficient resources while excluding smallholder farmers who lack essential financial resources.

3.9. Policy and Institutional Drivers of Adoption

The actual advantages of renewable energy integration for agricultural value chains depend on policies and institutional frameworks which either permit or restrict their implementation. Bathaei and Štreimikienė (2023) examined renewable energy together with sustainable agriculture indicators and found that policy support mechanisms including feed-in tariffs and investment tax credits and renewable energy certificates and rural energy grants serve as necessary conditions for successful renewable energy implementation. Fischer et al. (2006) demonstrated that policy stability together with policy predictability serves as essential requirements for making long-term investment decisions since policy changes and uncertainty diminish both investor trust and market adoption rates.

The institutional financing mechanisms serve as essential institutional components that determine how economies will perform. Hartung and Pluschke (2018) showed that small-scale farmers in developing regions face their main funding barrier when they try to obtain affordable financing despite solar-powered irrigation systems proving to be economically beneficial under regular conditions. The research by Durga et al. (2024) demonstrated that two main factors that restrict solar irrigation use in Sub-Saharan Africa include the absence of incentives and the discovery of hidden dangers. The research results showed that financing access together with risk management policies work better than technology subsidies in achieving positive outcomes.

The economic returns show strong dependency on regulatory frameworks which govern grid interconnection, net metering and renewable energy certification. Aziz et al. (2024) studied how renewable energy together with globalization and agricultural development affects sustainable economic growth while finding that institutional quality and governance effectiveness act as moderating factors between renewable energy investment and economic results. Janiszewska and Ossowska (2022) showed that biomass energy policies in the European Union created organized markets which use agricultural residues as their base material while developing regions face market development limitations since they lack regulatory systems for biomass collection and processing and energy conversion. The complete evaluation of renewable energy integration advantages requires researchers to examine institutional elements which affect the assessment process.

3.10. Research Gaps and Future Directions

Researchers now face research gaps which prevent them from achieving full understanding of how renewable energy systems will function within agricultural value chains despite existing evidence that shows economic and operational advantages of these systems. Pietrzak et al. (2025) conducted a systematic review of publication trends, key findings, and research gaps, identifying insufficient long-term impact assessment, limited standardization of economic evaluation methodologies, and inadequate attention to social and institutional dimensions as primary limitations. The existing practice of conducting short-term techno-economic analyses does not provide an accurate understanding of the technological and educational advancements which develop throughout extended periods.

The need for integrated value chain modeling represents a particularly critical gap. Existing studies predominantly examine renewable energy applications in isolation rather than analyzing integrated configurations which enable renewable energy substitution across multiple nodes to create combined benefits and associated trade-offs. Kumar et al. (2024) examined renewable energy in aquaculture and post-harvest technologies, documenting that solar and AI integration can optimize cold chain logistics, yet comprehensive assessments that cover production processing storage and distribution still remain uncommon. Future research should prioritize whole-value-chain analyses that capture indirect effects, multiplier impacts and long-term dynamic adjustments.

The current research studies face methodological restrictions since they fail to account opportunity costs they handle subsidies, policy incentives inconsistently and they restrict their economic evaluation methods to basic risk metrics. Batra (2023) studied renewable energy economics according to environmental protection needs and economic development requirements but he showed that traditional cost-benefit evaluations failed to assess external impacts and non-commercial assets and distributional impacts. The research needs standardized frameworks which combine sensitivity analysis and scenario modeling and distributional impact assessment to overcome its existing methodological restrictions.

4. Conclusion

This review shows that renewable energy integration in agricultural value chains provides economic advantages that are highly context-dependent since solar irrigation systems lead to reduced operational expenses and agrivoltaic systems produce dual income streams only when particular crop-and-climate conditions exist and solar cold storage systems decrease post-harvest losses. The benefits of these systems are not applicable to all situations since agrivoltaic systems decrease crop yields for plants that cannot tolerate shade while biomass energy production faces challenges from both feedstock transportation needs and required production capacities and high equipment expenses prevent smallholder farmers from using powerful new farming methods. The achievement of renewable energy potential requires the resolution of existing obstacles which include obstacles related to financing access, technical expertise, institutional backing and inconsistent policies that diminish investor trust. Future research should prioritize longitudinal impact assessments standardized economic evaluation methodologies, integrated value chain modeling that measures inter-node synergies, inter-node trade-offs and systemic effects. Policy interventions should focus on innovative financing mechanisms, risk mitigation instruments, capacity building programs and regulatory frameworks that create enabling environments for equitable renewable energy adoption in agricultural systems. The transition toward renewable energy-powered agricultural value chains creates an economic opportunity while establishing a governance challenge that needs joint efforts from technology finance and policy fields.

Compliance with Ethical Standards

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Disclosure of conflict of interest

The authors declare no conflict of interest.

Statement of ethical approval

The study conducted a literature review without involving human participants or animal subjects. The research therefore needed no ethical approval.

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