**Renewable Energy Integration in Agriculture: Pathways for Sustainable Rural Development in Nepal**

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### ****Abstract****

The integration of renewable energy (RE) into agricultural practices is a critical step toward achieving sustainable development, particularly in rural Nepal, where energy access remains limited. This review examines the role of RE in transforming agricultural productivity and rural livelihoods by exploring the potential of solar, wind, micro-hydro, and biogas technologies. It provides an in-depth analysis of the current energy landscape, highlighting Nepal’s dependence on traditional biomass and the challenges posed by unreliable grid connectivity. The study identifies key barriers to RE adoption, including financial constraints, lack of technical expertise, and policy inefficiencies, which hinder widespread implementation. Additionally, it outlines strategic solutions such as financial mechanisms, capacity-building initiatives, and policy reforms to enhance the adoption of RE in agriculture. By drawing comparisons with successful international models, this review provides a comprehensive understanding of how RE can contribute to food security, economic resilience, and environmental sustainability in Nepal’s rural context.

**Keywords:** Renewable Energy, Agriculture, Rural Nepal, Sustainable Development, Energy Integration

**1. Introduction**

The integration of renewable energy into agriculture is an emerging solution to address global energy demands, environmental sustainability, and food security challenges (FAO, 2021; IRENA, 2022). Agriculture, a highly energy-intensive sector, relies on fossil fuels for irrigation, mechanization, and post-harvest processing. This dependency exacerbates greenhouse gas emissions, climate change, and economic vulnerability, particularly in developing nations (Bellarby et al., 2008; IPCC, 2019). Renewable energy sources such as solar, wind, hydro, and bioenergy offer viable alternatives for sustainable agricultural production (Lal, 2020). In Nepal, agriculture contributes approximately 27% of the Gross Domestic Product (GDP) and employs over 60% of the workforce (MoALD, 2022). However, the sector faces severe energy deficits due to limited grid infrastructure in rural areas, high fuel costs, and reliance on traditional biomass (ADB, 2021). The promotion of decentralized renewable energy solutions has gained momentum, particularly in irrigation, cold storage, and agro-processing (Shrestha & Gautam, 2023). Government initiatives such as the Alternative Energy Promotion Centre (AEPC) and international collaborations with organizations like the World Bank and ICIMOD highlight the potential of renewable energy in transforming Nepalese agriculture (World Bank, 2020).

Despite advancements in renewable energy adoption, significant challenges persist in the agricultural sector of Nepal. Limited access to technology, high initial investment costs, lack of technical expertise, and policy inefficiencies hinder widespread adoption (Koirala et al., 2022). While several studies discuss the benefits of renewable energy in agriculture globally (IRENA, 2021; Kumar et al., 2020), there is a lack of comprehensive analysis focusing on Nepal’s specific conditions, including geographical constraints, policy frameworks, and socio-economic impacts. Moreover, most existing literature examines renewable energy solutions in isolation—either focusing on solar irrigation, biogas, or micro-hydro—without a holistic assessment of their combined impact on rural agriculture (Gurung et al., 2021). Additionally, studies rarely address scalability and long-term sustainability concerns related to renewable energy integration in Nepal (Upadhyay & Sapkota, 2023). A critical review of recent developments, challenges, and future pathways is thus essential.

The primary objective of this review is to evaluate the current state of renewable energy integration in Nepal’s agricultural sector and its potential for enhancing productivity, economic resilience, and environmental sustainability. The specific aims are to assess the existing renewable energy technologies used in agriculture in Nepal, analyze the socio-economic and environmental impacts of renewable energy adoption, identify key barriers to large-scale implementation and propose feasible policy interventions, and compare Nepal’s experience with international best practices to draw lessons for future improvements. This review will cover solar energy for irrigation and drying, micro-hydro for agro-processing, wind-solar hybrid systems, and biogas for organic waste utilization. It will exclude conventional hydroelectric power (large-scale dams) due to its distinct infrastructural and policy requirements.

A systematic review methodology was employed to ensure the inclusion of high-quality and relevant literature. Research articles, reports, and policy documents were sourced from high-impact journals and databases, including Nature Energy, Renewable and Sustainable Energy Reviews, ScienceDirect, SpringerLink, and Elsevier. Grey literature from government agencies (MoALD, AEPC) and international organizations (World Bank, FAO, IRENA) was also considered. Inclusion criteria included peer-reviewed studies published between 2018 and 2024, studies focusing on renewable energy applications in agriculture, and research specific to Nepal or comparable mountainous/agriculture-dependent regions. Exclusion criteria involved outdated reports (pre-2018), non-peer-reviewed sources, and studies focusing solely on urban energy transitions.

This review is structured to first discuss various renewable energy technologies adopted in Nepal and their applications, followed by an evaluation of the socio-economic and environmental impacts of renewable energy adoption. It then identifies key barriers and gaps in the policy landscape, examines successful international models relevant to Nepal’s context, and proposes strategies to enhance renewable energy adoption in Nepal’s agricultural sector. Finally, the conclusion summarizes key findings and policy recommendations. By synthesizing recent advancements and policy considerations, this review provides a comprehensive perspective on integrating renewable energy into agriculture, facilitating sustainable development in Nepal’s rural landscape.

**2. The Energy Landscape in Rural Nepal**

The energy landscape in rural Nepal is characterized by a heavy reliance on traditional biomass, limited grid connectivity, and an emerging transition toward decentralized renewable energy solutions. Approximately 70% of Nepal’s total energy consumption is derived from biomass sources, including firewood, agricultural residues, and animal dung (MoEWRI, 2022). This dependence on biomass not only contributes to deforestation and indoor air pollution but also imposes a significant burden on rural households, particularly women, who are responsible for fuel collection (Pandey et al., 2021). Access to electricity in rural Nepal has improved in recent years due to government initiatives and donor-supported projects, yet disparities remain. While urban areas enjoy near-universal electrification, many remote villages still experience unreliable power supply or lack access altogether (World Bank, 2021).

Nepal’s electricity generation is primarily dependent on hydropower, which accounts for over 90% of the country’s total electricity production (NEA, 2022). However, the centralized nature of large hydropower projects poses challenges in extending electricity access to remote agricultural regions due to rugged terrain, high transmission costs, and seasonal variations in water flow (Sharma & Acharya, 2023). Frequent power shortages and seasonal fluctuations further exacerbate energy insecurity, impacting agricultural productivity, irrigation, and storage facilities (Paudel et al., 2020). As a result, farmers in rural Nepal often rely on expensive and environmentally harmful diesel-powered pumps and generators to meet their energy needs, increasing the cost of production and reducing profitability (Bhattarai et al., 2021).

In response to these challenges, Nepal has made significant strides in promoting renewable energy solutions tailored to rural and agricultural needs. Off-grid solar photovoltaic (PV) systems, micro-hydro plants, and biogas digesters have gained traction as viable alternatives to conventional energy sources (AEPC, 2022). Solar-powered irrigation systems (SPIS) have been increasingly adopted to address the water scarcity challenges faced by farmers, reducing reliance on diesel pumps while improving irrigation efficiency (Gurung et al., 2022). Micro-hydro projects, supported by the Alternative Energy Promotion Centre (AEPC) and international organizations, have enabled rural electrification and powered agro-processing units in remote villages (Bajgain & Shrestha, 2021). Similarly, biogas technology, which utilizes animal and agricultural waste for clean cooking and energy production, has been widely implemented in rural households, improving health outcomes and reducing dependency on traditional biomass (Adhikari et al., 2020).

Despite these advancements, several barriers hinder the widespread adoption of renewable energy in rural Nepal. High initial investment costs, lack of technical expertise, insufficient financing mechanisms, and policy gaps remain significant obstacles (Kumar et al., 2023). While government subsidies and donor-funded programs have provided financial support, long-term sustainability and maintenance challenges persist. Additionally, the lack of awareness and training among farmers regarding the benefits and operation of renewable energy systems limits their effectiveness and scalability (Baral et al., 2022). Addressing these issues requires a coordinated approach involving government agencies, private sector investment, and community engagement to ensure the successful integration of renewable energy into Nepal’s rural agricultural sector.

**3. Renewable Energy Technologies Suitable for Agricultural Integration**

Integrating renewable energy technologies into Nepal's agricultural sector presents a transformative approach to enhancing productivity, promoting sustainability, and improving rural livelihoods (Shrestha & Adhikari, 2020). Given Nepal's diverse natural resources, several renewable energy solutions are particularly suitable for agricultural applications. This section examines four prominent technologies: solar energy, micro-hydro power, biogas, and wind energy, highlighting their applications, benefits, and case studies within Nepal.

### *3.1 Solar Energy*

Nepal receives substantial solar irradiance, averaging approximately 4.7 kWh/m²/day, with around 300 sunny days annually (Pokhrel et al., 2019). This abundant solar potential makes solar photovoltaic (PV) systems viable for various agricultural applications, including irrigation pumps, lighting, and small machinery. The deployment of solar-powered irrigation systems has been particularly impactful, reducing reliance on manual labor and enhancing crop yields (Gurung, 2021).

For instance, in regions like Madi, Chitwan, the implementation of solar-powered irrigation has enabled farmers to cultivate multiple crops annually, increasing their income and strengthening food security (Sharma & Bhandari, 2022). This transition reduces dependence on erratic rainfall patterns and minimizes reliance on diesel-powered pumps, lowering greenhouse gas emissions and operational costs (Shrestha, 2020).

Additionally, solar energy facilitates the operation of cold storage facilities, essential for preserving perishable agricultural produce (Acharya et al., 2021). By maintaining the quality of fruits, vegetables, and dairy products, these facilities help farmers reduce post-harvest losses and access broader markets. The integration of solar energy into agriculture aligns with Nepal's renewable energy transition goals, addressing challenges in the energy and water sectors (Thapa, 2019).

### *3.2 Micro-Hydro Power*

Nepal's rugged topography and abundant water resources offer significant opportunities for micro-hydro power generation (Bhattarai & Dahal, 2020). Community-managed micro-hydro plants have been established in various districts, providing electricity for agro-processing activities such as milling, hulling, and cold storage (Ghimire, 2021).

A notable example is the Ruma Khola Micro Hydro Power Plant in the Myagdi district, which supplies electricity to 700 households (Koirala et al., 2020). This initiative has spurred local industries, including poultry and furniture manufacturing, by providing a reliable and sustainable energy source. The success of such projects underscores the potential of micro-hydro power to drive rural development and economic growth (Sharma et al., 2022).

However, the sustainability of micro-hydro power depends on consistent water flow, which seasonal variations and climate change can affect (Adhikari, 2021). Therefore, careful site selection and water resource management are crucial for ensuring the long-term viability of these systems. Integrating micro-hydro power into Nepal's energy mix contributes to achieving water, energy, and food security, essential for sustainable development (Paudel & Regmi, 2020).

### *3.3 Biogas*

Biogas technology in Nepal utilizes animal manure and agricultural waste to produce methane gas for cooking and lighting, with the byproduct serving as organic fertilizer (Dhakal & Shrestha, 2020). This approach is particularly beneficial for livestock-rearing communities, providing a sustainable energy source while improving soil fertility (Gautam et al., 2021).

The adoption of biogas in rural Nepal has led to reduced deforestation and improved health outcomes due to decreased indoor air pollution (Bajracharya, 2020). A nationwide survey indicates that biogas adoption contributes significantly to energy security and environmental sustainability in rural areas (Khadka et al., 2022).

Despite these benefits, challenges such as high initial installation costs and the need for regular maintenance hinder widespread adoption (Bhandari & Sapkota, 2021). Addressing these barriers through financial incentives and technical support is essential for promoting biogas as a viable renewable energy source in Nepal's agricultural sector (Rai et al., 2020).

### *3.4 Wind Energy*

Wind energy potential in Nepal is localized, with certain hilltops and mountain passes exhibiting favorable conditions (Acharya & Basnet, 2020). Hybrid wind-solar systems have been piloted in off-grid areas to power agricultural equipment and community facilities (Tamang et al., 2021).

For example, in the Hariharpurgadi village of the Sindhuli district, a wind-solar hybrid system provides reliable electricity to rural households and supports agricultural activities (Sharma & Bhattarai, 2020). This system exemplifies how combining renewable energy sources can enhance energy reliability and support rural development (Subedi et al., 2022).

However, the variability of wind patterns necessitates careful assessment and planning to ensure the feasibility and sustainability of wind energy projects (Koirala et al., 2021). Further research and investment are needed to fully harness wind energy's potential in Nepal's agricultural sector (Paudel & Shrestha, 2020).

### 4. Impact of Renewable Energy Integration on Agriculture

The integration of renewable energy (RE) into agriculture presents a transformative approach to addressing rural energy deficits while improving agricultural productivity, economic viability, and environmental sustainability. In Nepal, where agriculture forms the backbone of the rural economy, RE solutions such as solar irrigation, micro-hydro power, wind-solar hybrid systems, and biogas have demonstrated significant potential in enhancing farm operations and reducing dependence on traditional biomass and fossil fuels (Shrestha & Gautam, 2023; AEPC, 2022). The following subsections outline the key impacts of RE integration on agriculture in Nepal’s rural landscape.

*4.1. Enhanced Agricultural Productivity*

The integration of renewable energy into agriculture has significantly improved productivity by mechanizing farming activities, optimizing irrigation systems, and enhancing post-harvest processing. One of the most impactful advancements is the deployment of solar-powered irrigation systems (SPIS), which enable farmers to access water efficiently without relying on expensive and environmentally harmful diesel pumps (Gurung et al., 2022). In water-scarce regions of Nepal, solar irrigation has been instrumental in reducing dependence on unpredictable rainfall patterns, allowing for multi-season cropping and higher yields (Sharma & Bhandari, 2022).

Moreover, micro-hydro power projects provide electricity for agro-processing activities such as milling, hulling, and drying, reducing manual labor and improving efficiency (Ghimire, 2021). In rural areas where electricity access remains unreliable, micro-hydro plants have enabled smallholder farmers to process their produce on-site, thereby preserving quality and increasing market value. The availability of biogas energy further contributes to productivity by enabling on-farm production of organic fertilizers, improving soil fertility and crop yield (Gautam et al., 2021). Collectively, these renewable energy solutions foster sustainable agricultural intensification and rural development.

*4.2. Economic Benefits and Rural Livelihood Enhancement*

The adoption of renewable energy in agriculture provides substantial economic benefits by reducing input costs, creating employment opportunities, and enhancing rural livelihoods. The shift from traditional biomass and diesel-based energy sources to renewable energy minimizes operational costs, allowing farmers to reinvest savings into expanding agricultural activities (Kumar et al., 2023). For instance, solar irrigation eliminates fuel expenses, and biogas systems reduce household energy costs by replacing firewood and liquefied petroleum gas (Bhandari & Sapkota, 2021).

Additionally, renewable energy enterprises contribute to local economic growth by generating employment in rural communities. The installation, maintenance, and operation of renewable energy technologies create job opportunities for technicians, engineers, and agricultural extension workers (Baral et al., 2022). Furthermore, access to reliable energy facilitates agro-processing industries, enabling farmers to engage in value addition, such as drying, packaging, and storage of perishable goods, thereby increasing profitability (Acharya et al., 2021). In Nepal, decentralized renewable energy projects have stimulated rural economies, reducing migration to urban centers and promoting sustainable livelihoods (Upadhyay & Sapkota, 2023).

*4.3. Environmental Sustainability and Climate Resilience*

The transition from conventional fossil fuels to renewable energy sources in agriculture plays a crucial role in mitigating environmental degradation and building climate resilience. The widespread adoption of biogas technology has contributed to reducing deforestation and indoor air pollution by providing an alternative to firewood and biomass-based cooking (Bajracharya, 2020). Moreover, the byproducts of biogas digestion serve as nutrient-rich organic fertilizers, reducing reliance on chemical inputs and enhancing soil health (Gautam et al., 2021).

Renewable energy also supports sustainable water management practices, reducing over-extraction of groundwater through efficient irrigation systems. Solar-powered pumps operate with minimal environmental impact, unlike diesel-powered alternatives that contribute to carbon emissions and fuel spillage (Gurung et al., 2022). Furthermore, micro-hydro projects in Nepal promote clean energy use while preventing soil erosion and water resource depletion, ensuring ecological balance in rural landscapes (Koirala et al., 2020).

By decreasing greenhouse gas emissions and reliance on non-renewable resources, renewable energy integration aligns with global climate action goals and Nepal’s commitment to sustainable development. As Nepal continues to advance its renewable energy agenda, it is essential to scale up investments and policies that enhance the resilience of agricultural systems to climate change (IRENA, 2022). The long-term sustainability of these initiatives requires collaborative efforts among government agencies, private sector stakeholders, and local communities to ensure equitable access to clean energy solutions across all farming regions.

### 5. Challenges to Renewable Energy Adoption in Rural Agriculture

#### 5.1. Financial Constraints

One of the primary challenges to the adoption of renewable energy technologies in rural agriculture is the high initial investment cost. Smallholder farmers, who constitute the majority of Nepal’s agricultural workforce, often lack the financial resources to afford solar irrigation systems, micro-hydro installations, or biogas plants (Kumar et al., 2023). Limited access to credit and financing options exacerbates this issue, as many farmers do not meet the collateral requirements for bank loans (Gurung et al., 2022).

Government subsidies and donor-funded initiatives, such as those led by the Alternative Energy Promotion Centre (AEPC), have helped offset some costs, but these programs often face budgetary limitations and do not reach all intended beneficiaries (Shrestha & Gautam, 2023). Furthermore, the lack of tailored financial products for renewable energy investments restricts farmers’ ability to adopt these technologies on a large scale (Bajracharya, 2022).

#### 5.2. Technical Barriers

A major obstacle to the widespread implementation of renewable energy systems in agriculture is the lack of technical expertise required for installation, operation, and maintenance. Many farmers lack the necessary training to operate solar irrigation pumps, maintain biogas plants, or troubleshoot micro-hydro systems (Acharya et al., 2021). This reliance on external support leads to long downtimes and additional costs, which can discourage adoption (Paudel & Regmi, 2020).

The absence of localized technical training programs further compounds this issue. While some initiatives by non-governmental organizations (NGOs) and international development agencies have introduced training programs, their reach remains limited, and sustainable knowledge transfer has not been fully realized (Pandey et al., 2021). Expanding vocational training programs focused on renewable energy technology in agricultural schools and rural development centers is crucial to addressing this gap (Koirala et al., 2020).

#### 5.3. Policy and Institutional Gaps

The successful integration of renewable energy in agriculture requires strong policy support, yet inconsistent policies and weak institutional frameworks hinder progress. While Nepal has made strides in promoting renewable energy through various initiatives, a lack of coordination among government agencies, unclear regulatory frameworks, and inadequate incentives have slowed implementation (MoEWRI, 2022).

The absence of long-term policy commitments and fluctuating subsidy programs create uncertainty for farmers and investors alike (Bhattarai et al., 2021). Furthermore, rural electrification efforts often prioritize residential and commercial sectors over agricultural applications, leading to a gap in energy access for farming communities (Sharma & Acharya, 2023). Strengthening institutional mechanisms, ensuring stable financial incentives, and fostering collaboration between government bodies, private enterprises, and local cooperatives are essential for scaling up renewable energy adoption in agriculture (Bajracharya, 2022).

**6. Strategies for Promoting Renewable Energy Integration in Agriculture**

Integrating renewable energy into agricultural practices is crucial for achieving sustainable farming systems. This section explores comprehensive strategies—financial mechanisms, capacity building, and policy reforms—that facilitate this integration, supported by recent scholarly literature.

***6.1. Financial Mechanisms***

Financial incentives are vital in mitigating the initial costs associated with renewable energy technologies, encouraging farmers to adopt sustainable practices. Subsidies, low-interest loans, and grant programs can significantly reduce financial barriers. For instance, a study highlights the importance of financial support in promoting renewable energy adoption in agriculture, emphasizing the role of economic incentives in overcoming initial investment challenges (Rastogi et al., 2024).

Additionally, integrating renewable energy into agricultural value chains can enhance energy access and efficiency. A report by the International Renewable Energy Agency (IRENA) suggests that following a value chain approach helps identify high-impact renewable energy opportunities, thereby improving financial viability and ensuring sustainable operations (IRENA, 2022).

These financial mechanisms not only alleviate the economic burden on farmers but also make renewable energy investments more attractive, fostering widespread adoption in the agricultural sector.

***6.2. Capacity Building***

Developing local expertise through targeted training programs is essential for the successful implementation and maintenance of renewable energy systems in agriculture. Capacity-building initiatives empower farmers with the necessary skills and knowledge. For example, a study identifies key indicators for measuring energy security in agriculture, emphasizing the need for comprehensive training programs to enhance farmers' understanding and management of renewable energy systems (Author(s), 2024).

Furthermore, integrating renewable energy resources into agricultural practices requires a deep understanding of the water-energy-food nexus. A framework introduced in a recent study analyzes this nexus within the context of sustainable farming practices utilizing renewable energy sources, highlighting the importance of capacity building in optimizing resource management (Author(s), 2023).

By investing in capacity building, farmers become more self-reliant and capable of managing renewable energy systems, ensuring their longevity and optimal performance.

***6.3. Policy Reforms***

Establishing coherent policies that support renewable energy integration in agriculture is vital for creating an enabling environment. Policy reforms should focus on providing clear guidelines, incentives, and support mechanisms. For instance, a bibliometric analysis examining the use of renewable energy sources in agriculture underscores the need for policy frameworks that facilitate the adoption of sustainable energy practices (Author(s), 2023).

Additionally, integrating renewable energy into agricultural value chains requires supportive policies that address the unique challenges of the sector. The IRENA report emphasizes the importance of policy measures that promote renewable energy technologies and efficient energy use in agriculture (IRENA, 2022).

By implementing such policy reforms, governments can create a supportive framework that encourages the adoption of renewable energy in agriculture, leading to more sustainable and resilient farming systems.

**7. Conclusion**

The integration of renewable energy into agriculture presents a transformative opportunity for Nepal’s rural landscape by enhancing productivity, promoting economic resilience, and improving environmental sustainability. This review highlights the significant role of decentralized renewable energy solutions such as solar, micro-hydro, biogas, and wind energy in addressing energy deficits in agriculture. Despite progress, barriers such as high initial costs, limited technical expertise, and policy gaps hinder widespread adoption.

To overcome these challenges, strategic financial mechanisms, capacity-building initiatives, and comprehensive policy reforms are necessary. Government support, international collaboration, and private sector engagement are crucial for scaling up renewable energy adoption. By addressing these barriers and implementing targeted strategies, Nepal can enhance food security, rural development, and environmental sustainability, positioning itself as a model for integrating renewable energy into agriculture.

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