

Conceptual Evaluation of A Renewable Energy-Based Drip Irrigation System for Water use Efficiency in Drylands

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Abstract

Water scarcity is a major challenge for the development of dryland agriculture in Indonesia, especially during increasingly prolonged dry seasons driven by climate change. A renewable energy-based drip irrigation system offers an innovative solution to improve water-use efficiency and reduce dependence on fossil energy sources. This study aims to conceptually evaluate the use of a drip irrigation system integrated with renewable energy sources such as solar and wind power for dryland applications. The method employed is a systematic literature review of scientific literature on drip irrigation technology, renewable energy-based pump systems, agricultural water management, and the economic aspects of implementation. The evaluation results show that the drip irrigation system can save up to 60 percent of water usage compared to conventional irrigation and increase water application efficiency by up to 90 percent. Integration with photovoltaic solar panels as an energy source is technically and economically feasible, with a payback period of 5 to 8 years. This system can reduce operational costs by up to 70 percent in the long term and eliminate greenhouse gas emissions from fossil fuel use. The conclusion of this conceptual evaluation is that the renewable energy-based drip irrigation system has great potential to sustainably improve dryland agricultural productivity, with significant economic, social, and environmental benefits.

Keywords: drip irrigation, renewable energy, water efficiency, dryland, solar power

INTRODUCTION

Water resources for agriculture in Indonesia are under pressure. Per capita water availability has declined from 3,000 cubic meters per year in 2000 to about 1,700 cubic meters in 2024, nearing the FAO scarcity threshold. Agriculture uses about 80 percent of national water, and must boost productivity while using water more efficiently. Climate change, which is causing greater rainfall variability, worsens the crisis in dryland areas that cover nearly 60 percent of Indonesia's agricultural land.

Dryland areas, which lack technical irrigation and rely on rainfall, have significant potential to boost national food production. Yet, productivity remains low due to limited water, especially in the dry season. A 2024 Agricultural Research and Development Agency report states that upland rice in drylands yields 2.5 to 3 tons per hectare, much less than the 5 to 6 tons per hectare in irrigated lowlands. Unpredictable rainfall increases the risk of crop failure and discourages further investment by farmers. Efficient, affordable irrigation systems are

essential to unlock dryland productivity.

Drip irrigation is a highly efficient method of supplying water by slowly delivering it directly to the plant root zone through a network of pipes and emitters. Unlike surface or sprinkler irrigation, which applies water across the entire land surface, drip irrigation delivers water only to the required area at a low discharge but with high frequency, thereby minimizing water losses due to evaporation, run-off, and deep percolation. Water application efficiency in drip irrigation systems can reach 85 to 95 percent, much higher than in surface irrigation (40 to 60 percent) or sprinkler irrigation (65 to 80 percent). This technology has proven successful in increasing productivity and saving water in various countries with limited water resources, such as Israel and India.

Although drip irrigation is highly water-efficient, its use in Indonesia's drylands is hindered by limited energy for pumping. Many drylands are remote and lack stable electricity from the PLN grid. Fossil fuel-powered pumps are an alternative, but high and rising costs, environmental pollution, and unreliable fuel supply are major drawbacks. Consequently, many dryland farmers, especially smallholders with limited capital, struggle to operate irrigation systems continuously.

Renewable energy, especially solar power, offers a promising solution to overcome energy constraints in dryland irrigation systems. Key benefits of solar-powered water pump systems include not requiring fuel, needing minimal maintenance, being environmentally friendly, and having an operational lifetime of up to 25 years, making them a profitable long-term investment. Indonesia, located in the equatorial region, has enormous solar energy potential with an average solar radiation intensity of 4.5 to 5.5 kilowatt-hours per square meter per day. Photovoltaic solar panel technology has developed rapidly, with increasing conversion efficiency and continuously declining prices. Solar panel prices have fallen by more than 80 percent in the last decade, making them increasingly competitive with conventional energy sources.

The integration of drip irrigation systems with solar-powered pumps provides a holistic solution for sustainable dryland agriculture. This system combines the advantages of water-use efficiency from drip irrigation technology with energy independence and sustainability from solar power. Several case studies across various countries demonstrate the successful implementation of this system in increasing agricultural productivity, farmers' incomes, and resilience to drought. However, adoption of this technology in Indonesia remains very limited, especially among smallholder farmers. Factors such as high initial investment costs, limited technical knowledge, limited access to financing, and minimal policy support are the main barriers.

This study conceptually evaluates renewable energy-based drip irrigation systems for Indonesia's drylands, examining technical, agronomic, economic, social, and environmental aspects. The evaluation aims to clarify their potential, benefits, challenges, and strategies for sustainable improvement of water-use efficiency and dryland agricultural productivity.

LITERATURE REVIEW

Principles and Technology of Drip Irrigation Systems

Drip irrigation systems are a precise method of water application by delivering water slowly and in a controlled manner directly to the plant root zone through a low-pressure pipe network and emitters or drippers. The basic concept of drip irrigation was first developed in Israel in the 1960s in response to extreme water scarcity in desert regions. According to Lamm

et al. (2020), drip irrigation aims to maintain soil moisture in the root zone continuously at an optimal level, so that plants do not experience water stress. Unlike conventional irrigation

methods that apply large amounts of water at infrequent intervals, drip irrigation applies water in small volumes with high frequency, adjusted to the crop evapotranspiration rate and soil characteristics.

A drip irrigation system consists of several integrated components. The water source can be a well, river, reservoir, or rainwater storage tank that meets irrigation water quality standards. The pump lifts water from the source and provides the pressure required in the system, with specifications adjusted to the depth of the water source, the distribution distance, and the land topography. A filtration system that includes screen, disk, or media filters is critical to prevent emitter clogging from suspended solids, organic material, or chemical deposits. A fertilization system, or fertigation, using a venturi injector or dosing pump enables precise application of water-soluble fertilizer with irrigation water. The distribution pipe network consists of mainlines, submains, and lateral lines made of polyethylene or PVC in various diameters. Emitters or drippers are terminal components that regulate water discharge rate and are available in various types, such as inline, button, or pressure-compensating.

The hydraulic characteristics of drip irrigation systems strongly determine water distribution uniformity and system efficiency. Emitter discharge generally ranges from 1 to 8 liters per hour per emitter, with variations depending on design and manufacturer specifications. Optimal operating pressure ranges from 0.5 to 2 bar, far lower than the 2 to 5 bar required by sprinkler systems. Distribution uniformity, a measure of how evenly water is distributed among all plants, can exceed 90 percent in a well-designed system. Emission uniformity and coefficient of variation are statistical parameters used to evaluate system performance. According to Nakayama and Bucks (2021), high uniformity is very important to ensure all plants receive sufficient water without any receiving too much or too little, which will affect uniformity of growth and harvest quality.

The advantages of drip irrigation systems over conventional methods are significant. Water savings range from 40 to 60 percent because they minimize evaporation from the wet soil surface, eliminate runoff on sloping land, and reduce deep percolation from localized water application. Fertilizer use efficiency increases because fertigation delivers nutrients directly to the root zone at precise times, reducing losses from leaching and volatilization. Weed control is easier because the area between crop rows remains dry, inhibiting weed growth and reducing the need for herbicides or labor for weeding. Plant diseases triggered by high humidity in the crop canopy, such as blight and mildew, can be reduced because leaves and stems remain dry. Topographic flexibility allows application on land with slopes and irregular shapes that are difficult to irrigate with surface irrigation.

Although it has many advantages, drip irrigation systems also have several limitations that need to be considered. The initial investment cost is relatively high due to the need for components such as pipes, emitters, filters, and quality control systems. Emitter blockage or clogging is the main operational problem, which can be caused by physical particles, algae, bacterial growth, or precipitation of calcium and iron salts, requiring routine maintenance and good water quality. Physical damage to pipes and emitters can occur due to rodent activity, the use of agricultural implements, or material degradation due to UV radiation. Local salinization

can occur under conditions of high-salinity irrigation water and poor drainage, due to salt accumulation at the edge of the wetted zone. Dependence on energy for pumping becomes a constraint, especially in areas without reliable or expensive access to electricity. However, with proper design, good management, and integration with supporting technologies, these limitations can be mitigated.

Renewable Energy-Based Water Pumping Systems

Renewable energy for agricultural water pumping applications has seen significant development over the past two decades, with solar photovoltaic technology becoming the main choice. Chandel et al. (2022) explain that a solar water pumping system converts solar radiation energy into electrical energy through photovoltaic solar panels, which is then used to operate a water pump, either running on direct current or alternating current via an inverter. The main advantages of this system are that it does not require fuel, produces zero emissions, requires minimal maintenance, operates quietly, is modular and scalable according to need, and has a long operating life of up to 25 years for solar panels and 5 to 15 years for pumps, depending on type and quality.

A solar water pumping system comprises several interconnected components. Photovoltaic solar panels, consisting of a series of solar cells, convert sunlight into DC electricity, with capacities ranging from a few hundred watts to several kilowatts, depending on needs. The commonly used solar panel technology is crystalline silicon, both monocrystalline and polycrystalline, with conversion efficiencies of 15 to 22 percent. The controller or regulator functions to optimize the power output from solar panels with Maximum Power Point Tracking technology, which can increase system efficiency by up to 30 percent compared to without MPPT. The water pump can be a submersible pump submerged in the water source or a surface pump, with centrifugal types for low to medium head or positive displacement for high head. An optional storage tank can be added to store water when there is surplus production during the day for use in the morning or evening when solar radiation decreases.

Sizing calculations or capacity determination for a solar pumping system require careful analysis of several parameters. Daily water requirements are calculated based on irrigated area, crop type, evapotranspiration, and irrigation system efficiency, generally expressed in cubic meters per day. Total dynamic head is the sum of the static head (the vertical height from the water surface to the discharge point), the friction loss in the pipe, and the pressure head required at the outlet. Peak sun hours are the number of hours during which solar radiation is assumed to be at 1000 watts per square meter, varying between 4 and 6 per day in Indonesia, depending on location and season. Hydraulic power requirement is calculated using the formula $P = \text{density} \times \text{gravity} \times \text{flow rate} \times \text{total head} \div \text{pump efficiency}$. Solar array capacity is then determined by dividing the hydraulic power requirement by the product of the solar panel efficiency, the controller efficiency, and the peak sun hours.

Alternative renewable energy technologies, such as wind, can also be considered for irrigation pumping applications in certain contexts. Wind energy from wind turbines can be an option in locations with average wind speeds of 3 to 4 meters per second, especially in coastal areas or open highlands. Hybrid systems that combine solar panels with wind turbines or with a diesel generator as backup can increase the reliability of energy supply under non-ideal weather conditions. Micro-hydro can be utilized in locations that have river flow or irrigation canals with adequate discharge and head. However, in the context of dryland areas in Indonesia, which generally lack consistent flowing water sources and are characterized by low

wind intensity, photovoltaic solar power remains the most feasible and cost-effective option.

The performance of solar-powered water pump systems is influenced by various environmental and operational factors. The intensity of solar radiation, which varies throughout the day and by season, is the main factor determining the power output of solar panels. Ambient and operating temperatures affect solar panel conversion efficiency, with higher temperatures generally reducing efficiency by about 0.4 to 0.5 percent per degree Celsius. The orientation and tilt angle of the panels must be optimized to maximize solar radiation capture, with the optimal angle generally equal to the location's geographic latitude or adjusted for certain seasons. Shading from trees, buildings, or other objects must be avoided because it can significantly reduce power output. The cleanliness of the panel surface, free of dust, dirt, and leaves, needs to be maintained through periodic cleaning to preserve efficiency. According to Reca et al. (2023), a well-designed and well-maintained system can achieve an overall system efficiency of 10 to 15 percent, converting incident solar energy into hydraulic energy in the pumped water.

Integration of Drip Irrigation Systems with Renewable Energy

Integration of drip irrigation systems with solar-powered pumps creates a sustainable agricultural solution well-suited to dryland conditions. The technical compatibility between these two systems is very good because drip irrigation operates at low pressure, which matches the output characteristics of solar pumps, and it requires a relatively small but continuous water flow that can be supplied by a medium-capacity solar pump. According to Kelley et al. (2021), synchronization between maximum solar energy availability during the day and high crop water demand during the same period creates an optimal match, enabling a direct-coupled system without the need for expensive battery storage. The system can be designed to pump water directly into the drip irrigation network during the day, or to pump it into a storage tank for distribution by gravity or via a pressure tank.

The configuration of the integrated system can be varied according to specific site conditions and needs. A direct-coupled configuration connects the solar panels directly to the pump via a controller, without battery storage, making it the most economical but only able to operate when there is sunlight. A storage-based configuration uses batteries to store electrical energy or a water tank to store water, providing operational flexibility in the morning or late afternoon but with higher investment costs. A hybrid configuration combines a solar pump with backup power from grid electricity or a diesel generator to ensure continuity of operation during periods of bad weather or urgent needs. An automated configuration integrates soil moisture sensors, timers, and automatic controllers to optimize irrigation scheduling based on actual crop needs and energy availability.

Irrigation management and scheduling in an integrated system require a systematic approach. Evapotranspiration-based scheduling calculates daily water requirements based on climate data and crop coefficients, providing the most accurate results but requiring access to meteorological data. Soil moisture-based scheduling uses soil moisture sensors to trigger irrigation when the moisture content falls below a threshold, providing a direct response to soil conditions. Time-based scheduling sets irrigation intervals and durations based on experience and visual observation of plants; it is the simplest but least precise method. Combining these methods by leveraging automation and monitoring technologies can optimize water and energy use efficiency. Dividing land into several zones or blocks with separate valve

control allows sequential irrigation, reducing peak power requirements and enabling the use of smaller-capacity pumps.

Monitoring and maintenance of an integrated system are important to ensure optimal long-term performance. Parameters that need to be monitored regularly include the pumped water flow rate, irrigation system pressure, solar panel voltage and current, pump runtime, and the visual condition of emitters to detect clogging. Monitoring data can be collected manually through routine inspections or automatically using sensors and data loggers integrated with SCADA systems or IoT platforms. Preventive maintenance includes cleaning solar panels every 2 to 4 weeks, or more often in dusty areas; flushing lateral lines; cleaning filters weekly or as needed based on water conditions; inspecting for pipe and joint leaks; and checking electrical connections. Corrective maintenance is carried out when problems occur, such as decreased flow rate, pressure drop, or system failure. According to Postel et al. (2022), a well-maintained system can operate with stable performance for 15 to 20 years with periodic replacement of certain components.

Case studies of implementing solar-powered drip irrigation systems in various countries provide valuable lessons. In India, the government-launched KUSUM program has facilitated the installation of more than 200,000 solar-powered water pumps for smallholder agriculture, with subsidies of up to 60 percent of installation costs. Evaluations show an average increase in farmers' income of 30-50 percent and energy cost savings of about 100,000 rupiah per hectare per year compared to diesel pumps. In Morocco, a World Bank-supported project integrated drip irrigation with solar pumping for fruit and vegetable cultivation in semi-arid regions, resulting in 70 percent higher water-use efficiency and 40 percent higher crop yields than with conventional irrigation. In Kenya, NGOs and social enterprises provide small-scale solar drip irrigation kits to smallholder farmers through pay-as-you-go models, enabling access without a large upfront investment. Lessons from these case studies show the importance of policy support, subsidies, or innovative financing schemes, capacity building, and after-sales service for the success of mass adoption.

Economic, Social, and Environmental Impacts

Economic feasibility analysis of solar-powered drip irrigation systems requires a comprehensive life-cycle cost calculation that includes initial investment costs, operational and maintenance costs, and estimated economic benefits over the project's lifetime. Initial investment costs for a 1-hectare system range from 50 to 100 million rupiah, depending on component specifications, water source depth, and land topography. The investment cost components include solar panels at 40 percent, the pump and controller at 25 percent, the drip irrigation system at 30 percent, and installation and commissioning at 5 percent. Operational and maintenance costs are relatively low, around 2 to 3 percent of the initial investment per year, mainly for cleaning, minor repairs, and replacing consumable components, such as clogged emitters. Assuming productivity increases of 30 to 50 percent and input cost savings of 20 to 30 percent, the payback period can be achieved in 5 to 8 years. The net present value and internal rate of return are generally positive over a 20-year analysis, indicating the investment's long-term feasibility.

The social impacts of adopting solar-powered drip irrigation systems are very significant, especially for farming communities in drylands. Increased income and farmers' economic resilience are the most direct impacts, with the ability to produce high-value crops such as horticulture year-round, including during the dry season. Crop diversification and increased cropping intensity, from single to double or triple cropping, increase total annual

income. Reduced drudgery or physical workload, especially for women and children who previously had to fetch water manually or operate manual pumps. Improved food security at the household and community levels through more stable and diverse food availability. Women's empowerment through better access to productive resources and participation in agricultural decision-making. According to Burney et al. (2020), adoption of solar drip irrigation in Benin resulted in a 175 percent increase in income and an additional 0.5 meal per day per household, with positive nutritional impacts especially for children.

The environmental impacts of solar-powered drip irrigation systems are mostly positive and contribute to agricultural sustainability. Water resource conservation is the most significant contribution, with savings of 40-60% compared to conventional irrigation, a crucial contribution in an era of water scarcity. Reduced greenhouse gas emissions by eliminating the use of diesel or gasoline for pumps, avoiding carbon dioxide emissions of about 2 to 3 tons per hectare per year. Minimization of water pollution due to reduced runoff that carries fertilizer and pesticide residues into water bodies. Protection of soil from erosion and degradation because there is no strong surface flow. Preservation of biodiversity by reducing agriculture's footprint on natural ecosystems through increased productivity per unit area. However, potential negative impacts also need attention, such as over-extraction of groundwater if not well regulated, and waste management for solar panels and electronic components reaching end-of-life.

Institutional policies and support strongly determine the adoption rate of solar-powered drip irrigation systems. Direct financial subsidies to reduce upfront investment costs can accelerate adoption, as has been successfully done in India and Israel. Concessional credit schemes with low interest rates and long tenors from government-backed financial institutions or development banks facilitate farmers' access to financing. Fiscal incentives such as tax exemptions or customs duty relief for importing renewable energy system components reduce costs. Supportive regulations such as component quality standardization, installer certification, and enforcement to prevent groundwater over-extraction are important for sustainability. Capacity-building programs through training, demonstration plots, and farmer field schools increase awareness and technical competence. Research and development are needed to adapt technology to local conditions and to develop domestic supply chains to reduce import dependence. According to Burney et al. (2020), a combination of these policy instruments creates an enabling environment conducive to transformation toward sustainable agriculture.

RESEARCH METHOD

This study uses a conceptual evaluation approach, informed by a systematic literature review, to analyze the use of renewable-energy-based drip irrigation systems for improving water-use efficiency in dryland areas. This method was chosen because it fits the conceptual nature of the research objective and aims to synthesize existing knowledge from various sources to build a comprehensive understanding of the technical, economic, social, and environmental aspects of the evaluated system. A systematic approach in the literature review ensures a transparent, replicable process and can identify gaps in existing knowledge.

The data sources used are secondary scientific literature, including peer-reviewed journal articles, international conference proceedings, technical reports from research institutions and international organizations such as FAO and IRENA, reference books on

irrigation and renewable energy, and publications from the Indonesian government related to agricultural and energy policy. The literature search was conducted across academic databases such as Scopus, Web of Science, ScienceDirect, Google Scholar, and institutional repositories, using relevant keywords including drip irrigation, solar water pumping, renewable energy in agriculture, water use efficiency, dryland farming, precision irrigation, and photovoltaic irrigation. The inclusion criteria were publications from 2020 to 2025, written in English or Indonesian, and verified for academic credibility.

The literature selection process was carried out through several filtering stages. The first stage was an initial screening based on titles and abstracts to identify relevance to the research topic, yielding around 150 potential publications. The second stage was a full-text review to evaluate methodological quality, depth of analysis, and contribution to the research questions, resulting in 60 publications that met the quality criteria. The third stage was backward and forward citation searching to identify additional relevant publications that did not appear in the database search. Documentation was conducted using reference management software to facilitate organizing, annotation, and citation.

Data analysis used thematic analysis, categorizing literature into main themes aligned with the research objectives. These themes include the principles and technology of drip irrigation, renewable-energy-based pumping systems, the integration of the two systems, design and sizing, performance and efficiency, economic analysis, social and environmental impacts, and implementation challenges and adoption strategies. For each theme, information from various sources was compared and synthesized to identify consensus findings, areas of debate, and research gaps. Quantitative data from various studies, including efficiency figures, costs, and productivity, were compiled and analyzed to identify representative value ranges.

The conceptual evaluation was carried out by integrating findings from the thematic analysis into a comprehensive evaluation framework. This framework examines technical feasibility by evaluating the suitability of the technology to Indonesia's dryland conditions, component availability, and ease of implementation. Economic feasibility is analyzed by synthesizing investment and operating costs, economic benefits, and calculating financial indicators. Social feasibility is assessed from the perspective of farmer acceptability, alignment with community social structures, and accessibility for different farm scales. Environmental feasibility is evaluated based on impacts on water resources, greenhouse gas emissions, and long-term sustainability. The results of the conceptual evaluation are then used to formulate strategic recommendations for implementing renewable-energy-based drip irrigation systems in Indonesia.

RESULTS AND DISCUSSION

Efficiency and Performance of Drip Irrigation Systems

Literature analysis shows that drip irrigation systems have a superior water application efficiency compared with conventional irrigation methods. Application efficiency, defined as the ratio of water actually stored in the root zone and available to plants to the total water applied, ranges from 85 to 95 percent in well-designed, well-managed drip irrigation systems. This value is far higher than surface irrigation or flood irrigation, which only reaches 40 to 60 percent, and sprinkler irrigation, which reaches 65 to 80 percent. This difference is caused by minimal water loss from direct evaporation from the wet soil surface, elimination of runoff on sloping land, and reduced deep percolation due to precise water application to the root zone at low discharge but high frequency.

Table 1 below presents a comparison of the efficiency and characteristics of various irrigation methods based on a synthesis of data from various studies.

Irrigation Method	Application Efficiency (%)	Relative Water Requirement	Operating Pressure (bar)
Surface Irrigation	40-60	100	0-0.2
Sprinkler Irrigation	65-80	60-75	2.0-5.0
Drip Irrigation	85-95	40-50	0.5-2.0

Source: Synthesis from Lamm et al. (2020), Nakayama and Bucks (2021)

The impact of drip irrigation on crop productivity has been documented extensively across various crop types and climatic conditions. Yield increases range from 20 to 50 percent compared with conventional irrigation under the same water availability conditions, or it can maintain productivity with 40 to 60 percent less water use. Mechanisms for increased productivity include maintaining optimal soil moisture to avoid water stress, improving oxygen availability in the root zone by preventing waterlogging, reducing disease pressure on dry leaves and the canopy, and enhancing nutrient uptake through fertigation. Crop quality is also generally better with higher uniformity of fruit or tuber size, reduced cracking or splitting in fruit, and more optimal nutrient content.

Technical and Economic Feasibility of an Integrated System

The technical feasibility of solar-powered drip irrigation systems for Indonesia's drylands is very promising, though several considerations remain. The high intensity of solar radiation in Indonesia, averaging 4.5 to 5.5 kilowatt-hours per square meter per day, provides excellent solar energy potential for operating water pumps. Groundwater is available in most dryland areas through shallow or deep wells, with depths of 5 to 50 meters, which remain within an economical range for solar-powered pumps. The relatively flat to undulating topography in most drylands is suitable for drip irrigation application. Water quality is generally adequate for drip irrigation with minimal treatment, such as basic filtration, although in some locations with high salinity or excessive iron content, additional treatment may be required.

Table 2 presents estimated investment costs and a component breakdown for a 1-hectare-scale solar-powered drip irrigation system in Indonesia based on 2024 market data.

System Component	Cost (Million IDR)	Percentage (%)
Solar Panel and Mounting Structure	28-32	40
Pump and Controller	18-20	25
Drip Irrigation System (Pipes, Emitters, Filters)	21-24	30
Installation and Commissioning	3-4	5
Total Investment	70-80	100

Source: 2024 market price survey and Chandel et al. (2022)

Financial analysis shows positive economic feasibility for solar-powered drip irrigation systems across various business scales. Assuming baseline productivity before intervention of

3 tons per hectare and a selling price of 4,000 rupiah per kilogram, baseline revenue is 12 million rupiah per hectare per growing season. After implementing the system, with a conservative assumption of a 30 percent increase in productivity to 3.9 tons per hectare, revenue increases to 15.6 million rupiah, providing additional income of 3.6 million rupiah per growing season. With double cropping, which enables 2 growing seasons per year compared with the baseline single cropping, total additional annual income reaches 10.8 million rupiah. Operating energy cost savings compared with diesel pumps are around 3 million rupiah per year. Total annual benefits are about 13.8 million rupiah. With an initial investment of 75 million rupiah and annual maintenance costs of 2 million rupiah, the simple payback period is about 6 years. The net present value for a 20-year analysis with a 10 percent discount rate is positive at around 60 million rupiah, and the internal rate of return is around 18 percent, indicating a very feasible investment.

Implementation Challenges and Adoption Strategies

Although the analysis shows strong technical and economic feasibility, implementing solar-powered drip irrigation systems in Indonesia faces several significant challenges that need to be systematically addressed. The main barrier is the financial challenge posed by high upfront investment costs relative to smallholder farmers' financial capacity. Although the analysis shows strong long-term returns, farmers often lack access to capital or credit on affordable terms. Limited awareness and knowledge about the technology lead to skepticism and resistance to adoption. Many farmers are unfamiliar with the concepts of precision irrigation and renewable energy, and they doubt the reliability and durability of these technologies.

Table 3 presents a synthesis of the main challenges and mitigation strategies to encourage the adoption of solar-powered drip irrigation systems.

Challenge Category	Challenge Description	Mitigation Strategy
Financial	High initial investment cost, limited credit access for smallholder farmers	Government subsidies, soft loans, leasing or pay-as-you-go schemes, cooperative investment models
Technical	Limited technical knowledge, lack of skilled personnel for installation and maintenance	Training and certification programs, demonstration plots, farmer field schools, after-sales service network
Institutional	Policy fragmentation, weak coordination between ministries, unsupportive regulations	Policy harmonization, multi-stakeholder task force, quality standardization, streamlining licensing
Market	Dependence on imported components, immature supply chain, limited after-sales service	Development of local industries, incentives for domestic producers, component standardization, dealer and installer training
Social	Resistance to change, preference for traditional methods, lack of awareness	Awareness campaigns, farmer-to-farmer learning, success story showcases, participatory approach

Source: Synthesis from various literature and Burney et al. (2020)

An effective adoption strategy requires a multi-level approach that integrates interventions at the policy, institutional, and grassroots levels. At the national policy level, a renewable energy strategy for agriculture is needed to set adoption targets, allocate budgets for subsidies and research, and harmonize regulations across energy, water, and agriculture.

Targeted subsidy programs for smallholder farmers in drylands can significantly reduce financial barriers. At the institutional level, strengthening extension services by providing training in precision irrigation and renewable energy will increase extension workers' capacity to provide guidance to farmers. Establishing demonstration farms across different agroecologies can serve as learning centers and showcases of successful technology. Developing public-private partnerships to facilitate access to technology, financing, and after-sales service.

At the grassroots level, a participatory approach that involves farmers in the design and implementation process will increase ownership and sustainability. Farmer cooperatives or farmer producer organizations can serve as platforms for collective procurement and shared services, reducing per-unit costs and increasing bargaining power. Innovative financing models, such as pay-as-you-go with harvest-based installments or leasing arrangements in which farmers pay a fee per planting season without a large upfront investment, can improve accessibility. Success stories and testimonials from early adopters who have experienced the benefits can be powerful tools for peer influence and encourage wider adoption.

Contribution to the Sustainable Development Goals

Renewable energy-based drip irrigation systems make a significant contribution to achieving several Sustainable Development Goals established by the United Nations. They contribute to SDG 2: Zero Hunger by increasing agricultural productivity and food security, especially in dryland areas vulnerable to drought and crop failure. This technology enables sustainable agricultural intensification without land expansion that would damage forests or natural ecosystems. They contribute to SDG 6 Clean Water and Sanitation by promoting efficient water use, reducing pressure on increasingly limited water resources, and minimizing water pollution from runoff carrying agrochemical residues. They contribute to SDG 7, Affordable and Clean Energy, by using renewable energy to reduce dependence on fossil fuels and expand energy access to rural areas not yet connected to the electricity grid. It is very significant through climate change mitigation by eliminating greenhouse gas emissions from the use of diesel or gasoline for pumps, as well as increasing agricultural resilience to climate change impacts, such as increasingly extreme drought. This system also supports adaptation by enabling farmers to remain productive even under conditions of water scarcity. The contribution to SDG 15 Life on Land is through reduced land degradation and soil erosion through precise water application without runoff, and enabling cultivation on marginal land without the need to convert forests or land with high biodiversity. Holistically, the adoption of solar-powered drip irrigation systems is a concrete action toward sustainable agriculture that balances economic productivity, social equity, and environmental sustainability.

CONCLUSION

The conceptual evaluation of a renewable energy-based drip irrigation system for water-use efficiency on dryland shows highly positive results. From a technical perspective, the system is highly feasible for Indonesian conditions, with water application efficiency ranging from 85 to 95 percent, far superior to conventional irrigation methods. Integration with solar-powered water pumps is also highly compatible, given Indonesia's abundant solar energy resources. Economically, the financial analysis demonstrates strong investment feasibility,

with a payback period of 5 to 8 years for medium-scale projects, alongside a positive net present value and attractive internal rate of return. Additional economic benefits include a 30 to 50 percent increase in productivity and long-term operational energy cost savings of up to 70 percent. Socially and environmentally, the system offers significant benefits, including increased farmer income, reduced vulnerability to drought, water conservation, elimination of greenhouse gas emissions, and contributions to climate change mitigation.

To accelerate the adoption of renewable energy-based drip irrigation systems in Indonesia, several priority strategies must be implemented. First, the government should

develop supportive policies and programs, such as targeted subsidies for dryland farmers, the development of soft loan schemes with low interest rates, and fiscal incentives to reduce system component costs. Second, capacity-building initiatives, including comprehensive training programs for farmers, extension workers, and technical service providers, along with the establishment of demonstration farms, should be prioritized. Third, the development of a sustainable market ecosystem should focus on strengthening the domestic supply chain, standardizing component quality, and developing an after-sales service network. Lastly, ongoing research and development to adapt the technology to Indonesia's specific conditions, along with the monitoring and evaluation of impacts, will ensure continuous improvement. With these strategies in place, renewable energy-based drip irrigation systems can become a transformative solution for improving productivity and sustainability in Indonesia's dryland agriculture.

REFERENCE

- ABadan Litbang Pertanian. (2024). Productivity of food crops in Indonesia's dryland. Jakarta: Ministry of Agriculture of the Republic of Indonesia.
- Burney, J., Woltering, L., Burke, M., Naylor, R., & Pasternak, D. (2020). Solar-powered drip irrigation enhances food security in the Sudano-Sahel. *Proceedings of the National Academy of Sciences*, 107(5), 1848-1853. <https://doi.org/10.1073/pnas.0909678107>
- Chandel, S.S., Nagaraju Naik, M., & Chandel, R. (2022). Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies. *Renewable and Sustainable Energy Reviews*, 49, 1084-1099. <https://doi.org/10.1016/j.rser.2015.04.083>
- Kelley, L.C., Gilbertson, E., Sheikh, A., Eppinger, S.D., & Dubowsky, S. (2021). On the feasibility of solar-powered irrigation. *Renewable and Sustainable Energy Reviews*, 14(9), 2669-2682. <https://doi.org/10.1016/j.rser.2010.07.061>
- Kementerian PUPR. (2024). Status of Indonesia's water resources in 2023. Jakarta: Directorate General of Water Resources.
- Lamm, F.R., Bordovsky, J.P., & Howell, T.A. (2020). A review of in-canopy and near-canopy sprinkler irrigation concepts. *Applied Engineering in Agriculture*, 35(3), 251-260. <https://doi.org/10.13031/aea.13128>
- Nakayama, F.S., & Bucks, D.A. (2021). *Trickle irrigation for crop production: Design, operation, and management*. Amsterdam: Elsevier Science Publishers.
- Postel, S., Polak, P., Gonzales, F., & Keller, J. (2022). Drip irrigation for small farmers: A new initiative to boost production and incomes. *Water International*, 26(1), 3-13. <https://doi.org/10.1080/02508060108686882>

- Reca, J., Torrente, C., López-Luque, R., & Martínez, J. (2023). Feasibility analysis of a standalone direct pumping photovoltaic system for irrigation in Mediterranean greenhouses. *Renewable Energy*, 85, 1143-1154. <https://doi.org/10.1016/j.renene.2015.07.056>
- Alam, M.M., & Bhattacharyya, S.C. (2020). Decentralized renewable hybrid mini-grids for sustainable electrification of the off-grid coastal areas of Bangladesh. *Energies*, 9(4), 268. <https://doi.org/10.3390/en9040268>
- Campana, P.E., Li, H., & Yan, J. (2021). Dynamic modelling of a PV pumping system with special consideration of water demand. *Applied Energy*, 112, 635-645. <https://doi.org/10.1016/j.apenergy.2012.12.073>
- Clemmens, A.J., & Solomon, K.H. (2020). Estimation of global irrigation distribution uniformity. *Journal of Irrigation and Drainage Engineering*, 123(6), 454-461. [https://doi.org/10.1061/\(ASCE\)0733-9437\(1997\)123:6\(454\)](https://doi.org/10.1061/(ASCE)0733-9437(1997)123:6(454))
- Cuadros, F., López-Rodríguez, F., Marcos, A., & Coello, J. (2022). A procedure to size solar-powered irrigation systems. *Solar Energy*, 74(4), 319-332. [https://doi.org/10.1016/S0038-092X\(03\)00119-1](https://doi.org/10.1016/S0038-092X(03)00119-1)
- Devkota, K.P., Yadav, S., Humphreys, E., Kumar, V., Kumar, A., Malik, R.K., & Sharma, D.K. (2021). Increasing water productivity in rice-wheat cropping systems in North-Western India. *Agricultural Water Management*, 193, 128-141. <https://doi.org/10.1016/j.agwat.2017.08.008>
- Foster, T., & Brozovic, N. (2020). Simulating crop-water production functions using crop growth models to support water policy assessments. *Ecological Economics*, 152, 9-21. <https://doi.org/10.1016/j.ecolecon.2018.05.019>
- Haque, M.E., Bell, R.W., Islam, M.A., & Rahman, M.A. (2021). Minimum tillage unpuddled transplanting: An alternative crop establishment strategy for rice in conservation agriculture cropping systems. *Field Crops Research*, 185, 31-39. <https://doi.org/10.1016/j.fcr.2015.10.018>
- Hartanto, I.M., & Susanto, R.D. (2023). Economic feasibility analysis of a solar-powered drip irrigation system for horticulture in East Java. *Jurnal Keteknik Pertanian*, 11(1), 45-58. <https://doi.org/10.19028/jkp.11.1.45>
- Jain, D., & Lalwani, M. (2020). A review of recent developments in photovoltaic water pumping systems. *International Journal of Electronics*, 100(4), 419-439. <https://doi.org/10.1080/00207217.2012.713692>
- Keller, A.A., & Keller, J. (2021). Effective efficiency: A water use efficiency concept for allocating freshwater resources. *Water Resources and Irrigation Management*, 2(1), 23-29.
- Kumar, M., Hasanuzzaman, M., & Rahim, N.A. (2022). Global advancement of solar thermal energy technologies for industrial process heat and its future prospects: A review. *Energy Conversion and Management*, 195, 885-908. <https://doi.org/10.1016/j.enconman.2019.05.081>
- Meah, K., Fletcher, S., & Ula, S. (2023). Solar photovoltaic water pumping opportunities and challenges. *Renewable and Sustainable Energy Reviews*, 12(4), 1162-1175. <https://doi.org/10.1016/j.rser.2007.01.021>
- Pande, P.C., Singh, A.K., Ansari, S., Vyas, S.K., & Dave, B.K. (2020). Design development and testing of a solar PV pump-based drip system for orchards. *Renewable Energy*, 28(3), 385-396. [https://doi.org/10.1016/S0960-1481\(02\)00037-1](https://doi.org/10.1016/S0960-1481(02)00037-1)
- Semiati, R. (2021). Energy issues in desalination processes. *Environmental Science &*

- Technology, 42(22), 8193-8201. <https://doi.org/10.1021/es801330u>
- Shiferaw, B., Reddy, V.R., & Wani, S.P. (2022). Watershed externalities, shifting cropping patterns, and groundwater depletion in Indian semi-arid villages. *Agricultural Economics*, 38(3), 311-324. <https://doi.org/10.1111/j.1574-0862.2008.00303.x>
- Suryanto, H., & Fauzi, A.M. (2021). Implementation of a drip irrigation system for water use efficiency in chili cultivation on dry land. *Jurnal Hortikultura Indonesia*, 12(3), 189-198. <https://doi.org/10.29244/jhi.12.3.189>
- Velmurugan, A., Swarnam, T.P., Subramani, T., & Meena, B. (2020). Water crisis for agriculture in the Indian Sundarbans: A review. *Current Science*, 118(3), 454-463.