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OPTIMIZATION OF SOLAR PUMPING SYSTEMS IN THE ORIENTAL REGION OF MOROCCO: TECHNICAL, ECONOMIC, AND ENVIRONMENTAL PERFORMANCE

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A B S T R A C T

The adoption of photovoltaic (PV) solar pumping systems provides a sustainable and efficient solution for agriculture, particularly in regions with high solar potential such as Morocco. This study develops an optimization model that integrates field surveys, climatic data, and mathematical modeling to enhance the technical, economic, and environmental performance of PV water pumping. Results indicate that optimized solar pumping systems can reduce energy costs by up to 75%, with a payback period ranging from 2 to 8 years, depending on the energy source replaced. Additionally, environmental analysis highlights a significant reduction in CO_2 emissions, estimated between 480 and 720 tons per year for 60 studied farms. Recommendations include energy surplus valorization, smart pump adoption, and climate forecasting integration to promote large-scale PV implementation and reduce reliance on fossil fuels.

1. INTRODUCTION

Agriculture, a fundamental pillar of the global economy, is facing growing challenges related to the scarcity of water resources and rising energy costs (Food and Agriculture Organization of the United Nations [FAO], 2020; International Renewable Energy Agency [IRENA], 2023a). These issues are particularly critical for water pumping systems used in agricultural irrigation, which have traditionally been powered by fossil fuels, resulting in high costs and a significant carbon footprint. To address these constraints, photovoltaic (PV) solar pumping has emerged as a sustainable alternative, reducing operating costs and CO_2 emissions (Baba & Al-Habaibeh, 2017; (Mergoul et al., 2018). This technology is actively promoted in Morocco as part of the Green Morocco Plan and the Generation Green Strategy, particularly in the Oriental region (Ministry of Agriculture, Maritime Fisheries, Rural Development and Water and Forests, 2022).

Despite its advantages, large-scale adoption of solar pumping remains hindered by technical challenges, notably the optimal sizing of systems (flow rate, power, and total dynamic head) and the valorization of energy surpluses. Previous studies have often been limited to economic analyses or isolated case assessments (Kodji Deli et al., 2018; Mendes de Jesus et al., 2024), without

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considering the interactions between technical, economic, and environmental aspects. Moreover, the valorization of energy surpluses, such as the use of excess energy for water storage or crop drying, remains underexploited.

This study stands out through the development of a multi-criteria optimization model that evaluates technical (flow rate, total dynamic head, PV power), economic (investment costs, payback period), and environmental (CO_2 emissions reduction) dimensions. This model, applied to data from 60 agricultural holdings already equipped with photovoltaic systems in the Oriental region, also incorporates the valorization of energy surpluses to enhance the resilience of agricultural enterprises. This innovative approach identifies concrete strategies to improve the profitability and sustainability of agricultural enterprises while contributing to national objectives for energy transition and agricultural sector resilience (Carricondo-Antón et al., 2023; Rana et al., 2023a).

The objectives of this study are multifaceted and aim to address the previously identified challenges. They are as follows:
Develop a multi-criteria optimization model: This model integrates technical (flow rate, total dynamic head, PV power), economic (investment costs, payback period), and environmental (CO_2 emissions reduction) dimensions to provide a comprehensive reference framework for optimal sizing of solar pumping systems.

Optimize the configuration of solar pumping systems: This optimization aims to determine the optimal system parameters (panel power, pump type, total dynamic head, and required flow rate) to minimize investment and operating costs while ensuring maximum efficiency.

Valorize energy surpluses produced by PV systems: Identify strategies for reusing excess energy, particularly for water storage, crop drying, and the processing of agricultural products, to enhance the profitability of farms.

Provide strategic recommendations for policymakers and farmers: These recommendations aim to improve the large-scale adoption of solar pumping systems by developing strategies based on concrete evidence and field simulations.

2. MATERIALS AND METHODS

2.1. Study Context

The study was conducted in the Oriental region of Morocco, which is characterized by a high solar potential (over 3,000 hours of annual sunshine). The region hosts a wide variety of agricultural holdings, including small (< 6 ha), medium (6-15 ha), and large (> 20 ha) farms. The selection of this region aligns with the aim of promoting renewable energy in line with the objectives of the Green Morocco Plan and the Generation Green.

2.2. Data Collection

Sample: The sample consists of 60 agricultural farms distributed across the provinces of Oujda, Guercif, and Figuig. These farms were randomly selected to ensure representativeness of agricultural practices and farm sizes.

Data Sources: The data were collected from the following sources:

- Field surveys: Semi-structured interviews with farmers and technicians regarding the characteristics of photovoltaic systems (power, flow rate, total dynamic head (TDH), costs, and irrigation practices).
- Climatic data: Data from PVGIS and reports from the Ministry of Agriculture, particularly on sunshine, temperature, and the evolution of local climatic conditions (Baba & Al-Habaibeh, 2017).

These data were used to parameterize the optimization models and evaluate the performance of photovoltaic systems.

2.3. Methodology for PV System Optimization

A multi-criteria optimization model was designed to optimize the power of photovoltaic panels and the capacity of pumps. This methodology follows the steps outlined below:

1. Analysis of water needs: Determining water needs for each farm based on the flow rate and total dynamic head (TDH).
2. Calculation of required power: The power of PV panels is calculated according to the following equation:

$$P = \frac{Q.H.\rho.g}{\eta} \qquad (1)$$

Where :
P = required power,
Q = flow rate (m³/h),
H = total dynamic head (m),
η = pump efficiency.

Cost Optimization
Cost optimization involves minimizing investment and operating costs while maximizing the return on investment (ROI) according to the following equation:

$$\max ROI = \frac{B - (C_{inv} + C_{exp})}{C_{inv} + C_{exp}} \qquad (2)$$

ROI: Return on Investment (system profitability).
B: Net benefit generated (savings and surplus valorization).

C_{inv}: Initial investment cost (purchase and installation of equipment).
C_{exp}: Operating and maintenance cost (cleaning, maintenance, and inverter replacement).

where "Benefits" represents the financial gains, and "Total Costs" refers to the combined investment and operational costs.

2.4. Valorization of Energy Surpluses

The energy surpluses generated by photovoltaic systems are utilized through the following strategies:

- Water storage: Excess energy is used to pump and store water in reservoirs to meet future water demand.
- Energy storage: Surplus energy can be stored in batteries for later use, although this strategy is relatively costly.
- Direct use: The energy is directly utilized for agricultural activities such as crop drying or agri-food processing (Rana et al., 2023a).

2.5. Tools and Evaluation Indicators

Tools used:

- PVGIS: Used for the estimation of local photovoltaic production.
- Excel: Used for financial calculations (ROI, investment costs, payback period) and optimization of system sizing (Benali & Kousksou, 2022).

Evaluation indicators:

- Technical performance: Volume of water pumped, energy produced, and the rate of coverage of water needs.
- Economic performance: Installation costs, internal rate of return (IRR), and cost savings compared to diesel-based systems.
- Environmental performance: Reduction of CO_2 emissions and the impact on environmental sustainability.

3. RESULTS

3.1. Technical Performance

This section explores the technical performance of photovoltaic solar pumping systems installed in the Oriental region. It analyzes the energy needs of agricultural holdings in terms of total dynamic head (TDH), pump flow rate, and operating durations, while highlighting the implications for system sizing.

3.1.1. Energy Production and Coverage

The analysis of energy performance reveals an average annual production of 740,975 kWh, enabling energy coverage of 120% of irrigation needs. This overproduction is more pronounced in small farms (< 6 ha), where production significantly exceeds demand. This overproduction is linked to the oversizing of photovoltaic systems, which are designed to compensate for variability in solar irradiation (Merida-García et al., 2023c).

The figure 1 illustrates the energy production and energy needs of agricultural holdings according to farm size.

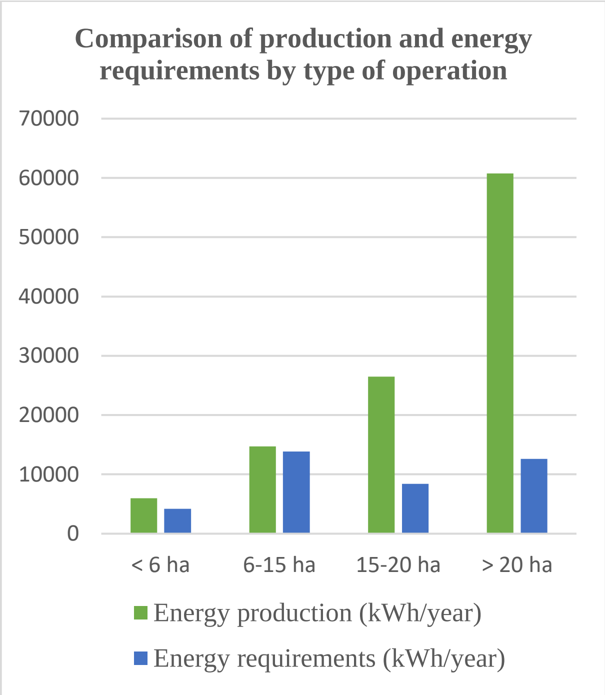

Figure 1. Comparison of production and energy requirements by type of operation

3.1.2. Performance, Efficiency, and Reliability of Solar Pumping Systems

a. System Performance and Efficiency

Photovoltaic solar pumping systems demonstrate remarkable technical performance, with energy coverage ranging from 120% to 567%, depending on the size of the farms. This overproduction represents an opportunity for energy surplus valorization, which can be utilized for water storage and the powering of agricultural equipment (e.g., crop drying) (Rana et al., 2023b). However, system efficiency is affected by the accumulation of dust on the panels, which can lead to a 20% reduction in overall performance (IRENA, 2023b). Currently, manual cleaning of panels is required, but the implementation of automatic cleaning systems could further enhance overall system performance (Carricondo-Antón et al., 2023).

b. System Reliability and Availability
Solar pumping systems have an availability rate of 98%, indicating high reliability compared to other regions in Africa, where the average availability rate is 95% (Baba

& Al-Habaibeh, 2017).The primary causes of system interruptions are:

- Inverter failures: Affecting 5% of the farms due to voltage surges or failures in electronic components.
- Dust accumulation: Reported by 20% of the farms, this leads to a reduction in energy production. Automatic cleaning solutions are recommended to ensure continuous energy availability (Baba & Al-Habaibeh, 2017).

The figure 2 below illustrates the key performance indicators of the photovoltaic system:

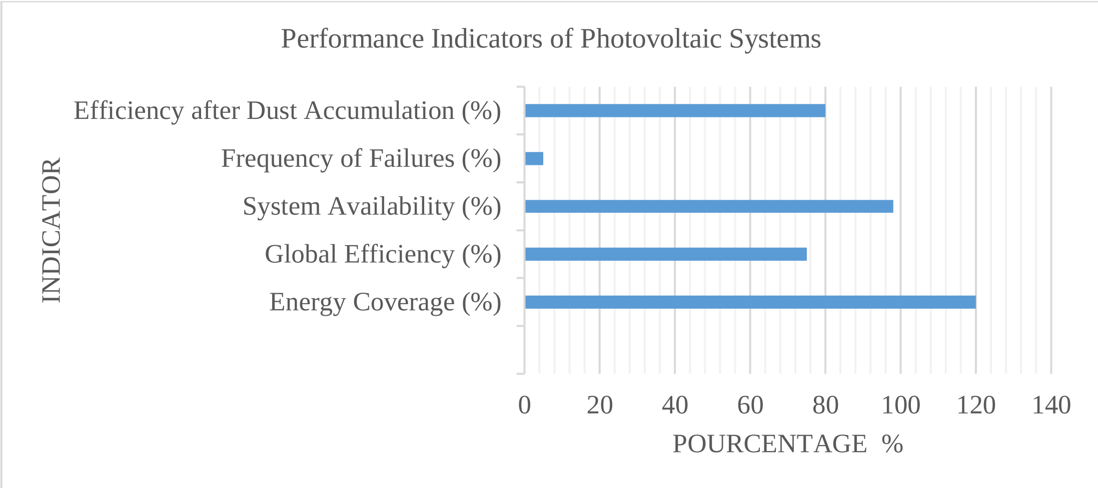

Figure 2. Key Performance Indicators of the Photovoltaic System

3.1.3. Pumping Capacity and Flow Rates of Systems

The pump flow rate is a crucial parameter for technical performance. The (Table 1) indicate that flow rates vary from 5 m³/h to 50 m³/h, depending on the size of the farm and the total dynamic head (TDH), which ranges between 30 and 120 meters (Mergoul et al., 2018).

Table 1. The size of the farm and the total dynamic head (TDH)

Farm Size	Average Flow Rate (m³/h)	TDH (m)
Small farms (< 6 ha)	5 to 10 m³/h	30 - 60
Medium farms (6-15 ha)	10 to 20 m³/h	40 - 80
Large farms (> 20 ha)	20 to 50 m³/h	60 - 120

Key Observations:

- Small farms: The flow rates are relatively low (5 to 10 m³/h), and the TDH is below 60 m, reducing the power required for the pumps.
- Large farms: The demand for higher flow rates (20 to 50 m³/h) and a TDH of up to 120 m justifies the need for larger photovoltaic system configurations (Carricondo-Antón et al., 2023).

3.2. Economic Performance

The analysis of the economic performance of photovoltaic (PV) solar pumping systems in agricultural holdings in the Oriental region of Morocco demonstrates significant economic advantages. Thanks to the reduction in energy costs, optimization of initial investments, and a competitive payback period (PBP), these systems offer a cost-effective alternative to diesel and electric pumps. This section presents an innovative analysis of costs, savings, and the impact of subsidies.

3.2.1. Investment Costs

The initial investment cost of solar pumping systems includes the purchase and installation of photovoltaic panels, inverters, pumps, and support systems. The analysis of 60 agricultural holdings studied shows that total investment costs vary according to farm size (Table 2).

Table 2. Investment Structure and Cost Distribution for Solar Pumping Systems by Farm Size

Farm Size	Total Investment Cost (MAD)	Share of PV Panels (%)	Share of Inverters (%)	Share of Pumps & Support (%)	Installation Costs (%)
Less than 6 ha	75,000 to 100,000	50%	25%	15%	10%
6 to 15 ha	100,000 to 150,000	45%	25%	20%	10%
15 to 20 ha	150,000 to 200,000	40%	30%	20%	10%
More than 20 ha	200,000 to 300,000	40%	30%	20%	10%

Analysis and Interpretation:
Investment costs increase with the size of the farm. Photovoltaic panels represent the largest share (40% to 50%) of the total cost, followed by inverters (25% to 30%) (IRENA, 2022). This increase is attributed to the use of larger capacity pumps and inverters for larger farms.

3.2.2. Operating and Maintenance Costs

Operating and maintenance costs vary depending on the size of agricultural holdings (Table 3). These costs include:

- Preventive maintenance costs (panel cleaning, inverter inspections)
- Inverter replacement costs (every 7 to 10 years)
- Panel cleaning fees (manual or automated).

Analysis and Interpretation:
Maintenance costs increase with the size of the farm. Farms larger than 20 ha record annual maintenance costs of 5,000 to 8,000 MAD (Rana et al., 2023b). These costs are related to the need to clean more panels and maintain higher-capacity inverters.

Table 3. Operation and Maintenance Costs of Solar Pumping Systems by Farm Size

Farm Size	Preventive Maintenance Costs (MAD/year)	Inverter Replacement (every 7-10 years, MAD)	Panel Cleaning Fees (MAD/year)
Less than 6 ha	1,000 to 2,000	15,000	500 to 800
6 to 15 ha	2,000 to 3,000	20,000	800 to 1,000
15 to 20 ha	3,000 to 5,000	25,000	1,000 to 1,500
More than 20 ha	5,000 to 8,000	30,000	1,500 to 2,000

3.2.3. Economic Profitability and Return on Investment (ROI)

Economic profitability is measured by the return on investment (ROI) and the payback period (PBP).

Analysis and Interpretation:
The data presented in Table 4 shows that Small farms (< 6 ha) record a higher ROI (25%) and a shorter payback period (1.1 years) (Carricondo-Antón et al., 2023). This profitability is due to the 75,000 MAD subsidy and the lower maintenance costs. Larger farms have an ROI of 15% and a payback period of 2.7 years, which remains highly competitive compared to other energy systems (Merida-García et al., 2023b). These results are consistent with studies conducted by IRENA (2023b) and analyses by Rana et al. (2023a), which reported similar results in solar pumping projects deployed in Morocco and North Africa (Mergoul et al., 2018).

Table 4. Economic Performance of Solar Pumping Systems by Farm Size

Farm Size	Return on Investment (ROI, %)	Payback Period (years)
Less than 6 ha	25%	1.1
6 to 15 ha	20%	2
15 to 20 ha	18%	2.3
More than 20 ha	15%	2.7

3.3. Environmental Performance of Solar Pumping Systems

The evaluation of the environmental performance of photovoltaic (PV) solar pumping systems focuses on their ecological impact at both local and global levels. This analysis highlights their contribution to the ecological sustainability of agricultural holdings in the Oriental region of Morocco.

The main criteria include CO_2 emissions reduction, water resource management, and electronic waste reduction.

3.3.1. Reduction of CO_2 Emissions

The use of photovoltaic solar pumping systems significantly reduces CO_2 emissions compared to diesel-powered pumping systems (Table 5). According to IRENA (2021), CO_2 emission reductions are proportional to the size of agricultural holdings.

Analysis and Interpretation:
Farms larger than 20 ha avoid CO_2 emissions of 30 to 50 tCO_2/year, which is equivalent to the emissions of 8 to 12 vehicles (Kodji Deli et al., 2018). Large agricultural holdings thus make a significant contribution to carbon neutrality.

Table 5. Environmental Impact of Solar Pumping Systems by Farm Size

Farm Size	Amount of CO_2 Avoided (tCO_2/year)	Equivalent in Vehicle Emissions (cars/year)
Less than 6 ha	8 to 12 tCO_2/year	Equivalent to 2 to 3 vehicles
6 to 15 ha	12 to 20 tCO_2/year	Equivalent to 3 to 5 vehicles
15 to 20 ha	20 to 30 tCO_2/year	Equivalent to 5 to 8 vehicles
More than 20 ha	30 to 50 tCO_2/year	Equivalent to 8 to 12 vehicles

3.3.2. Water Resource Management

Optimizing water usage is essential to ensure the resilience of agricultural holdings in the face of drought. Solar pumping systems are often combined with localized irrigation technologies and moisture sensors, which help reduce water consumption.

Analysis and Interpretation:
Farms larger than 20 ha achieve a 25% to 30% reduction in water consumption (Table 6), thanks to the integration of localized irrigation systems (FAO, 2020). This reduction aligns with observations from the FAO (2022) in semi-arid regions.

Table 6. Water Savings and Consumption Reduction Achieved by Solar Pumping Systems by Farm Size

Farm Size	Water Saved (m³/year)	Reduction in Water Consumption (%)
Less than 6 ha	150 to 250 m³/year	10 to 15%
6 to 15 ha	250 to 500 m³/year	15 to 20%
15 to 20 ha	500 to 800 m³/year	20 to 25%
More than 20 ha	800 to 1,200 m³/year	25 to 30%

3.3.3. Component Lifespan and Recycling

Photovoltaic panels and inverters are the main components of solar pumping systems (Table 7). Their lifespan and recyclability play a crucial role in reducing electronic waste.

Table 7. Lifespan and Recycling Potential of Key Components in Solar Pumping.

Component	Average Lifespan	Recycling Rate (%)
Photovoltaic Panels	20 to 25 years	90%
Inverters	7 to 10 years	75%

Systems Analysis and Interpretation:
Photovoltaic panels are recyclable at a rate of 90%, with an average lifespan of 20 to 25 years, according to the European Photovoltaic Industry Association (IRENA, 2021). Inverters, which need to be replaced every 7 to 10 years, require a specific recycling process, but their recycling rate (75%) remains high compared to other electronic devices.

Summary of Environmental Performance:
The environmental performance of solar pumping systems shows clear advantages in terms of reducing CO_2 emissions, promoting sustainable water management, and reducing electronic waste. These systems support carbon neutrality objectives and resilience to drought, especially for large-scale agricultural operations.

4. DISCUSSION

The study of photovoltaic (PV) solar pumping systems in Morocco highlights significant strategic contributions in technical, economic, and environmental aspects. By combining the analysis of actual payback periods, reductions in CO_2 emissions, and energy overproduction, this study reveals the potential for optimization and transformation of agricultural practices in Morocco, aligning with broader techno-economic assessments of integrated PV-water systems for arid region agriculture (Yan et al., 2023).

4.1. Technical Performance

The technical performance of solar pumping systems is characterized by energy overproduction ranging from 120% to 567% of the irrigation needs of agricultural holdings. This overproduction results from the oversizing of installations, which ensures the continuity of energy supply even during periods of low solar irradiation. This situation is particularly advantageous for small farms (< 6 ha), which can redirect these surpluses to other agricultural activities (Merida-García et al., 2023c).

Key Technical Challenges:

- Inverter Failures: Occurring in 5% of the farms, these failures are often caused by voltage fluctuations or defects in electronic components (Rana et al., 2023b).
- Dust Accumulation on Panels: Dust, reported by 20% of the farms, can reduce energy production by 20% (Gasque et al., 2024b).

Technical Recommendations:

- Automation of Panel Cleaning: Use of robotic cleaning systems to reduce efficiency losses caused by dust accumulation.
- Improvement of Inverter Reliability: Implementation of preventive maintenance programs to minimize downtime and increase system availability.

4.2. Economic Performance

The economic performance of solar pumping systems in Morocco reveals high profitability, thanks to reduced operating costs and strategic public subsidies. Actual payback periods (Table 8) range from 1.1 to 2.7 years, contrary to the 5 to 9 years initially anticipated, demonstrating a much faster return on investment than expected (FAO, 2022).

Table 8. Financial Viability of Solar Pumping Systems by Farm Size

Farm Size	Return on Investment (ROI, %)	Payback Period (years)
Less than 6 ha	25%	1.1
6 to 15 ha	20%	2
15 to 20 ha	18%	2.3
More than 20 ha	15%	2.7

Economic Recommendations:

- Acceleration of Subsidies: Accelerate the disbursement of subsidies to reduce farmers' reliance on self-financing.
- Promotion of Access to Bank Financing: Facilitate access to funding through programs like Tamwil Al Fallah, which support rural development.
- Valorization of Energy Surpluses: Use energy surpluses to power crop dryers or store water to increase farm profitability (Merida-García et al., 2023a)

4.3. Environmental Performance

The environmental performance of PV systems is characterized by a 100% reduction in CO_2 emissions compared to diesel systems. This reduction amounts to 43 tCO_2/year per farm, which equates to 860 tCO_2 over 20 years (Carricondo-Antón et al., 2023).

Co-Benefits of Environmental Performance:

- Reduction of Air Pollution: Decrease in PM2.5 and PM10 particles, improving air quality and the health of farm workers.
- Reduction of Noise Pollution: PV systems operate silently, offering better working conditions.

Environmental Recommendations:

- Carbon Credit Monetization: Monetize the reduction of 860 tCO_2 through carbon credit markets.
- Promotion of Environmental Awareness: Raise awareness among farmers to encourage the adoption of PV systems (Rana et al., 2023a)

5. CONCLUSION

Photovoltaic (PV) solar pumping systems in Morocco represent a strategic and sustainable solution for the modernization of agriculture. This study, based on the analysis of 60 agricultural holdings in the Oriental region, highlights remarkable technical, economic, and environmental performance, that supports Morocco's renewable energy and agricultural development goals (Ministry of Agriculture, Maritime Fisheries, Rural Development and Water and Forests, 2022).

On the technical front, PV systems ensure energy overproduction (120% to 567% of irrigation needs), enabling the valorization of energy surpluses through water storage or powering agricultural equipment (Merida-García et al., 2023a). Technical improvements, such as preventive maintenance for inverters and the automation of panel cleaning to mitigate dust-related efficiency losses (Gasque et al., 2024b), can further enhance system reliability.

On the economic front, the study revealed reduced payback periods (1.1 to 2.7 years) due to the combination of public subsidies and fuel cost savings, demonstrating economics competitive with international benchmarks for similar systems in arid regions (Gasque et al., 2024a). This rapid profitability is a key driver for the adoption of solar pumping systems. Furthermore, access to financing through the Tamwil Al Fallah program serves as a critical lever to reduce dependence on self-financing.

On the environmental front, PV systems contribute to carbon neutrality by avoiding 43 tCO_2/year per farm, equivalent to 860 tCO_2 over 20 years (Carricondo-Antón et al., 2023). This reduction in emissions, combined with the absence of noise and fine particles, improves air quality and working conditions for farm workers.

Summary: This study confirms that photovoltaic solar pumping systems are a high-performance, sustainable alternative to diesel pumps. By reducing operating costs, generating environmental benefits, and accelerating investment recovery, these systems offer a promising solution for Morocco's agricultural policies. To reinforce their adoption, it is recommended to streamline subsidy payments, facilitate access to bank financing, and monetize carbon credits as a new source of revenue for farmers aligning with strategies to enhance the sustainability of agricultural water management (Rana et al., 2023a).

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