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Economic and Environmental Implications of Solar Photovoltaic Pumping Systems in Agri-Water Management: A Case Study of Marrakesh Orchards

Implications Économiques et Environnementales des Systèmes de Pompage Solaire Photovoltaïque dans la Gestion Agricole de l'Eau : Étude sur l'Arboriculture de la Région de Marrakech

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Economic and Environmental Implications of Solar Photovoltaic Pumping Systems in Agri-Water Management: A Case Study of Marrakesh Orchards

Abstract

This study investigates the adoption of solar photovoltaic (PV) pumping systems in Moroccan orchards and its implications for groundwater sustainability and agricultural productivity in the context of escalating water scarcity due to climate change. This study focuses on examining the impact of solar PV systems on groundwater depletion, agricultural yields, environmental sustainability, and economic viability, particularly in a semi-arid region like Marrakesh. Adopting a qualitative case study design, the research involved 15 semi-structured interviews with orchard managers from small, medium, and large farms that have implemented solar pumping systems for over a year. The data analysis included thematic analysis, comparing the effects of solar-powered irrigation systems with traditional diesel-powered methods. The results reveal that while solar PV systems significantly reduce energy costs and greenhouse gas emissions, their impact on groundwater levels varies by farm size, with larger farms facing higher risks of over-extraction. Furthermore, the reliability of water supply provided by solar energy did not lead to noticeable improvements in crop yields, indicating that solar technology alone may not enhance agricultural productivity without improvements in irrigation efficiency. The study emphasizes the critical need for targeted policies and support mechanisms to ensure sustainable water management and agricultural practices in regions facing similar environmental challenges. Moreover, this research contributes to the broader discourse on renewable energy adoption in agriculture by providing empirical evidence on the operational impacts of solar PV systems on water resource management. The practical implications of this study are significant for the agri-sector, offering guidance on the potential and limitations of solar energy in sustaining agricultural productivity and groundwater resources.

Keywords : Solar Photovoltaic Pumping Systems, Groundwater Sustainability, Agri-Productivity, Renewable Energy, Moroccan Orchards.
JEL Classification : Q15, Q25, Q42, Q56
Paper type: Empirical research

1. Introduction

Morocco's farming sector continues to demonstrate resilience despite ongoing challenges posed by climatic variability, including a significant shortfall in rainfall, irregular distribution patterns, and rising temperatures that reflect a broader trend of unfavorable weather over the past five years, four of which have been marked by drought (Bentaleb & Taki, 2024a; Bentaleb & Taki, 2023a). Agriculture remains a cornerstone of societal development in Morocco, employing approximately two-fifths of the national labor force, with an even greater impact in rural regions, underscoring the sector's crucial role in driving socio-economic progress (Bentaleb & Taki, 2023b). However, Morocco, as a semi-arid country, faces severe water stress, a challenge that is further exacerbated by climate change. Since 1960, the per capita availability of renewable water resources has drastically declined from 2,560 m^3 to approximately 620 m^3 per year, approaching the threshold of absolute water scarcity at 500 m^3 per person per year (Tsakok, 2023; World Bank, 2022). Historically, Morocco relied on traditional water management structures like khetarras[1] and seguias[2], along with large-scale public schemes such as the El-Kansara Dam (World Bank, 1980). Nonetheless, declining rainfall and the rising demand for non-agricultural water due to urbanization and industrialization have necessitated a shift towards non-conventional water sources, such as desalination, wastewater reuse, and rainwater harvesting (Tsakok, 2023; World Bank, 2022). This shift requires a significant overhaul of the energy sector to align with the country's decarbonization goals. Furthermore, the anticipated increase in urban water demand by 60%-100% in major cities by 2050, along with projected temperature rises across North Africa, underscores the urgency of adopting sustainable water management practices (World Bank Group, 2017; World Bank Group, 2021). In response to these challenges, the intersection of water resource management and agricultural sustainability in Morocco is becoming increasingly critical. Agriculture, which consumes a significant portion of the country's water resources, faces mounting pressure from water scarcity and the need for sustainable energy solutions. This has spurred growing interest in solar energy pumping systems as a sustainable and cost-effective alternative to traditional water extraction methods. By harnessing the Kingdom's abundant solar resources, these systems offer a promising solution for agricultural irrigation, aligning with the global shift towards renewable energy and sustainable farming practices. This paper investigates the transformative potential of solar energy pumping in Moroccan agri-production, focusing on its implications for water table conservation—a key factor in sustaining agricultural productivity amid escalating climate challenges. The study explores the convergence of technological innovation, water resource management, and agricultural sustainability, providing a comprehensive analysis of solar energy pumping as a viable strategy for enhancing agricultural resilience in Morocco. Additionally, this research contributes to the broader discourse on sustainable agricultural practices in semi-arid regions. Concentrating on Morocco's agri-sector, the study explores how solar energy pumping can help mitigate the impacts of water scarcity and climate change, ensuring long-term agricultural sustainability and food security. The findings of this research hold significance not only for Morocco but also for other countries facing similar environmental and agricultural challenges, offering important guidance for policymakers, practitioners, and researchers focused on sustainable agriculture and water management. This article is structured to first provide a thorough review of the literature on the impacts of climate change on agriculture and the role of agri-solar energy pumping. It then articulates the research questions and outlines the methodology employed in the study. Following this, the data collection process

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[1] Ancient underground irrigation systems consisting of a network of wells and channels used to extract and transport groundwater in arid regions.
[2] Traditional open-channel irrigation systems designed to distribute water from rivers or springs to agricultural fields in semi-arid areas.

is detailed, and the empirical findings are presented. The discussion section critically examines these findings, drawing out the implications for the agricultural sector. Finally, the article concludes by synthesizing the results and suggesting directions for future research.

2. Literature Review

2.1. Effects of Climate Change on Agriculture

Climate change, marked by rising precipitation, temperatures, and CO2 concentrations, is significantly transforming global agriculture (Christensen & Hewitson, 2007; Yadav et al., 2020). The increase in CO2 levels and climatic shifts are altering crop growth patterns, thereby affecting global food production. While global warming may initially boost crop yields, this positive trend is expected to reverse by 2030, leading to a net decline in agricultural output (Mendelsohn et al., 1994; Mendelsohn, 2014; Mahendra, 2011). Additionally, climate change exacerbates pest proliferation, which in turn increases the need for pesticides, carrying consequential environmental and societal impacts (Malla, 2009). In Morocco, a semi-arid country with highly variable rainfall, these climate-induced challenges are particularly acute. Since 1960, the per capita availability of renewable water resources has sharply declined, nearing the absolute water scarcity threshold of 500 m³ per person per year (World Bank, 2022). This scarcity is further intensified by climate change, which is projected to increase water stress in the coming decades (World Bank, 2022). Climate change is significantly impacting agricultural practices by increasing extreme weather events, such as droughts, floods, and heatwaves, which are altering crop productivity and amplifying water scarcity issues (Kalogiannidis et al., 2024; Ma & Rahut, 2024; Tang et al., 2024). Historically, Morocco has implemented various structures to manage its scarce water resources, such as khetarras and seguias, along with large-scale infrastructure like the El-Kansara Dam (World Bank, 1980). However, with declining rainfall and rising non-agricultural water demand driven by urbanization and industrialization, Morocco is increasingly relying on non-conventional water sources, necessitating a significant overhaul of its energy sector (World Bank, 2022). The projected 60%-100% rise in urban water demand in major cities by 2050, combined with anticipated temperature increases across North Africa, further compounds the challenge. These climatic changes are not only reducing crop yields but are also adversely affecting livestock, thereby exacerbating the challenges faced by the agricultural sector (World Bank Group, 2017; World Bank Group, 2021). This situation underscores the urgent need for adaptive and sustainable agricultural practices to ensure food security and maintain ecological balance.

2.2. Agri-Solar Energy Pumping

The growing demand for agricultural power, particularly in developing countries, has intensified the exploration of alternative energy sources such as solar power (Korpale et al., 2016). Solar-powered pumping systems, primarily based on photovoltaic technology, convert solar energy into electrical energy to lift water, thereby providing a reliable energy supply and improving access to water for irrigation (NSW Farmers & GSES, 2015). In Morocco, where agriculture accounts for approximately 85% of water consumption, there has been a significant shift towards solar water pumping systems, especially following the reduction of subsidies for traditional diesel and gasoline (Mergoul et al., 2018). This shift mirrors a global trend towards solar-powered irrigation, with notable expansions in countries like Bangladesh and India, and is particularly significant in Morocco (Kunen et al., 2015; Mergoul et al., 2018). The adoption of solar pumping systems is driven by their cost-effectiveness and profitability, contributing substantially to socio-economic development (NSW Farmers & GSES, 2015). These systems typically comprise a PV array, motor (DC/AC), pump, water storage tank, and electrical wiring, and they offer multiple benefits, including enhanced crop yields, improved food security, and

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resilience against environmental stressors. Additionally, they provide ancillary benefits for human health, education, and poverty reduction, reflecting a broader shift towards more sustainable and efficient agricultural practices (NSW Farmers & GSES, 2015). The critical importance of water and electricity in agriculture is underscored by their roles in boosting productivity and alleviating poverty (United Nations, 2012; FAO, 2011). Solar-powered pumping systems, with their sustainable design, address the rising electricity demands in agriculture (Chandel et al., 2015). The environmental advantages of these systems over conventional diesel pumps are well-documented, including reduced greenhouse gas emissions and enhanced energy security (Korpale et al., 2016; Suojanen et al., 2017). Although initial installation costs can be high, the long-term benefits—such as increased crop resilience, poverty alleviation, and food security—make solar power pumping a viable and increasingly favored option in agriculture (Foster & Cota, 2014; Mergoul et al., 2018; Zhou & Abdullah, 2017).

3. Research Questions

This study aims to evaluate the impact of solar photovoltaic pumping systems on groundwater conservation and agricultural sustainability in Moroccan arboriculture production. Solar PV pumping systems represent a crucial technological advancement in addressing water scarcity in agriculture, particularly in semi-arid regions like Morocco. The research model integrates recent technological advancements in solar energy with sustainable agricultural practices, grounded in theoretical frameworks and empirical findings from the literature, to assess the potential benefits and challenges of solar-powered irrigation. The existing literature suggests that solar PV systems offer a more sustainable alternative to traditional diesel-powered pumps by reducing the energy intensity of water pumping, thereby mitigating groundwater over-extraction (Chel & Kaushik, 2011; Chilundo et al., 2019). Diesel-powered pumps, which are often inefficient, contribute to accelerated groundwater depletion due to high operational costs that encourage over-pumping (Foster & Cota, 2014). Additionally, solar energy pumping systems provide a consistent and reliable water supply, which is crucial for maintaining crop health and improving yields. The efficiency of solar pumps, along with their independence from fuel availability, ensures adequate irrigation during critical growth periods, thereby enhancing agricultural productivity (Kelley et al., 2010; Narale et al., 2013; Verma et al., 2021). Furthermore, solar PV systems are recognized for their potential to reduce greenhouse gas emissions and energy consumption, making them integral to sustainable agriculture (Chel & Kaushik, 2011; Das & Mandal, 2018). Replacing diesel pumps with solar-powered alternatives significantly lowers the carbon footprint of orchards, contributing to broader sustainability goals (Foster & Cota, 2014). From an economic perspective, despite the higher initial costs, solar PV systems offer long-term savings on energy expenses, making these systems economically viable for farmers. Reductions in fuel costs, along with subsidies and incentives for renewable energy adoption, enhance the profitability of farms using solar-powered irrigation (Abousserhane et al., 2022; Narale et al., 2013). In light of these considerations, the following research questions have been formulated:

- ***RQ1****: How do solar energy pumping systems affect groundwater depletion in Moroccan orchards compared to traditional diesel-powered irrigation systems?*
- ***RQ2:*** *What is the impact of adopting solar PV pumping systems on agricultural yields in terms of reliability and efficiency of water supply?*
- ***RQ3:*** *In what ways do solar-powered irrigation systems contribute to the long-term sustainability of agricultural practices by lowering the carbon footprint associated with conventional energy sources?*
- ***RQ4:*** *How do solar energy pumping systems influence the economic viability of arboriculture farming by lowering energy costs and reducing dependency on fossil fuels?*

The research will draw on data from Moroccan agricultural enterprises that have implemented solar energy pumping systems, offering insights into the integration of renewable energy within agriculture. The study will specifically focus on the sustainability and economic viability of these systems in water-scarce regions.

4. Research Methodology

The qualitative case study design is a well-established research approach that enables an in-depth exploration of complex issues within their real-life contexts. This methodology is particularly valuable in situations where the boundaries between the phenomenon being studied and its context are not clearly defined, making it ideal for exploratory, explanatory, and descriptive research (VanWynsberghe & Khan, 2007). The qualitative case study design supports the integration of various data sources, such as interviews, observations, and document analysis, which enhances the depth and validity of research findings (Da Silva et al., 2020; Elshall et al., 2020). This approach is especially suited for investigating intricate interactions between environmental, economic, and social factors, as seen in the study of agricultural sustainability and water management (Lampridi et al., 2019). In the context of the current research, a qualitative case study design is particularly appropriate due to the need to explore the impact of solar energy systems on agricultural sustainability and groundwater conservation within a specific socio-environmental setting. Morocco's unique environmental challenges, particularly the severe water scarcity in agri-regions, necessitate a research approach capable of capturing the nuances of local practices and their broader sustainability implications (Gallagher & Gergel, 2017; El-Nashar & Elyamany, 2023). By focusing on Moroccan orchards that have implemented solar energy pumping systems, this case study aims to generate in-depth insights into the effectiveness of these systems in conserving groundwater and promoting agricultural sustainability. This approach allows for a comprehensive understanding of the lived experiences of the farmers and other stakeholders, capturing the socio-environmental dynamics at play (Mason et al., 2020; Onghena et al., 2019). The qualitative case study not only contributes to the theoretical understanding of sustainable agri-practices in semi-arid regions but also provides practical insights for policymakers and practitioners involved in the promotion of renewable energy technologies in agriculture (Lai & Roccu, 2019). Semi-structured interviews are a qualitative research method combining predetermined questions with flexibility, allowing for rich, detailed data collection while maintaining comparability across participants (Kallio et al., 2016; Roulston & Choi, 2018). Careful selection of interview techniques is crucial for effectively gathering key data in qualitative research, which is particularly suited for exploring subjective aspects of social phenomena without relying on predetermined variables or hypotheses (Bentaleb & Taki, 2023c; Bentaleb & Taki, 2024b; Bhatta, 2018; Elhami & Khoshnevisan, 2022; Queirós et al., 2017).

4.1. Scope and Data

To gather in-depth insights into the adoption and impact of solar energy pumping systems in the Marrakesh region, 15 semi-structured interviews were conducted with orchard managers between July 22 and 26, 2024. Each manager had a minimum of five years of experience in managing farm operations, ensuring familiarity with both traditional and solar-powered irrigation systems. Interviews, lasting 60 to 80 minutes, allowed for comprehensive discussions on key themes. Details about the interviewees are provided in Table 2. To ensure accuracy, all interviews were audio recorded and supplemented with note-taking. Following the interviews, manual transcription was performed to capture nuances, enhancing the reliability of the subsequent thematic analysis. Farms were strategically selected to include 5 small (≤ 5 ha), 5 medium-sized (5 to 20 ha), and 5 large farms (> 20 ha). All farms had solar systems installed for over a year, ensuring familiarity with their operations across agricultural cycles.

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The interview protocol focused on five themes addressing sustainability, productivity, environmental impact, economic viability, and the broader implications of adopting renewable energy in agriculture (**Table 1: Semi-structured interview guide**

Themes	Questions
Theme 1: Groundwater Depletion and Management	- Since adopting solar energy pumping systems, what changes, if any, have you observed in groundwater levels? - How do these changes compare with your experiences using diesel-powered pumps? - What strategies, if any, have you implemented to manage groundwater more sustainably with the new system?
Theme 2: Agricultural Yield and Irrigation Efficiency	- How has the reliability and consistency of your water supply evolved since the implementation of solar photovoltaic pumping systems? - In what ways have the adoption of solar PV pumping systems influenced your agricultural yields? Could you provide specific examples or data that illustrate these changes? - Have you observed any enhancements in your irrigation practices following the transition to solar energy? If so, can you detail these improvements, particularly in terms of efficiency and effectiveness? - Since the installation of the PV system, have you observed any changes in the duration or frequency of your irrigation sessions? Please elaborate on any differences noted. - Following the integration of the solar PV system, have there been any adjustments made to the power settings of your irrigation pump? What factors influenced these changes? - How has the introduction of the PV system influenced your irrigation scheduling? Specifically, how have the start and stop times of irrigation been affected? - Have you maintained the same water storage capacity since the installation of the PV system, or have there been modifications? What prompted any changes made? - What has been the economic impact of transitioning to solar PV pumping systems on your production costs, particularly in relation to irrigation and overall farm management?
Theme 3: Environmental Sustainability	- What environmental benefits have you observed since using solar-powered irrigation? - Have you noticed any reductions in greenhouse gas emissions or other environmental improvements? - Are there any environmental challenges or drawbacks you have encountered with the use of solar energy?
Theme 4: Economic Viability and Cost-Benefit Analysis	- Can you describe the initial investment costs associated with switching to solar energy pumping systems? - Have you experienced any long-term savings on energy costs since adopting solar technology? - How has the transition to solar energy affected the overall economic sustainability of your farm?
Theme 5: Adoption and Future Prospects	- What motivated you to adopt solar energy pumping systems for your farm? - What barriers, if any, did you encounter during the adoption process? How did you overcome them?

	- What are your future plans regarding the use of solar energy in your farming operations? - What support or incentives would you recommend to encourage wider adoption of solar technology in agriculture?

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Table 1: Semi-structured interview guide

Themes	Questions
Theme 1: Groundwater Depletion and Management	- Since adopting solar energy pumping systems, what changes, if any, have you observed in groundwater levels? - How do these changes compare with your experiences using diesel-powered pumps? - What strategies, if any, have you implemented to manage groundwater more sustainably with the new system?
Theme 2: Agricultural Yield and Irrigation Efficiency	- How has the reliability and consistency of your water supply evolved since the implementation of solar photovoltaic pumping systems? - In what ways have the adoption of solar PV pumping systems influenced your agricultural yields? Could you provide specific examples or data that illustrate these changes? - Have you observed any enhancements in your irrigation practices following the transition to solar energy? If so, can you detail these improvements, particularly in terms of efficiency and effectiveness? - Since the installation of the PV system, have you observed any changes in the duration or frequency of your irrigation sessions? Please elaborate on any differences noted. - Following the integration of the solar PV system, have there been any adjustments made to the power settings of your irrigation pump? What factors influenced these changes? - How has the introduction of the PV system influenced your irrigation scheduling? Specifically, how have the start and stop times of irrigation been affected? - Have you maintained the same water storage capacity since the installation of the PV system, or have there been modifications? What prompted any changes made? - What has been the economic impact of transitioning to solar PV pumping systems on your production costs, particularly in relation to irrigation and overall farm management?
Theme 3: Environmental Sustainability	- What environmental benefits have you observed since using solar-powered irrigation? - Have you noticed any reductions in greenhouse gas emissions or other environmental improvements? - Are there any environmental challenges or drawbacks you have encountered with the use of solar energy?
Theme 4: Economic Viability and Cost-Benefit Analysis	- Can you describe the initial investment costs associated with switching to solar energy pumping systems? - Have you experienced any long-term savings on energy costs since adopting solar technology? - How has the transition to solar energy affected the overall economic sustainability of your farm?

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Theme 5: Adoption and Future Prospects	- What motivated you to adopt solar energy pumping systems for your farm? - What barriers, if any, did you encounter during the adoption process? How did you overcome them? - What are your future plans regarding the use of solar energy in your farming operations? - What support or incentives would you recommend to encourage wider adoption of solar technology in agriculture?

Source: Authors

Table 2: Respondent Details and Interview Information

Respondent Code	Farm Size	Years of Experience	Length of Interview (minutes)
1	Small (≤ 5 ha)	≥ 15 years	60
2	Small (≤ 5 ha)	10-15 years	75
3	Small (≤ 5 ha)	≥ 15 years	80
4	Small (≤ 5 ha)	≥ 15 years	65
5	Small (≤ 5 ha)	10-15 years	70
6	Medium (5 to 20 ha)	5-10 years	60
7	Medium (5 to 20 ha)	5-10 years	65
8	Medium (5 to 20 ha)	10-15 years	80
9	Medium (5 to 20 ha)	10-15 years	75
10	Medium (5 to 20 ha)	≥ 15 years	70
11	Large (> 20 ha)	≥ 15 years	65
12	Large (> 20 ha)	10-15 years	80
13	Large (> 20 ha)	≥ 15 years	60
14	Large (> 20 ha)	10-15 years	75
15	Large (> 20 ha)	10-15 years	70

Source: Authors

4.2. Research model

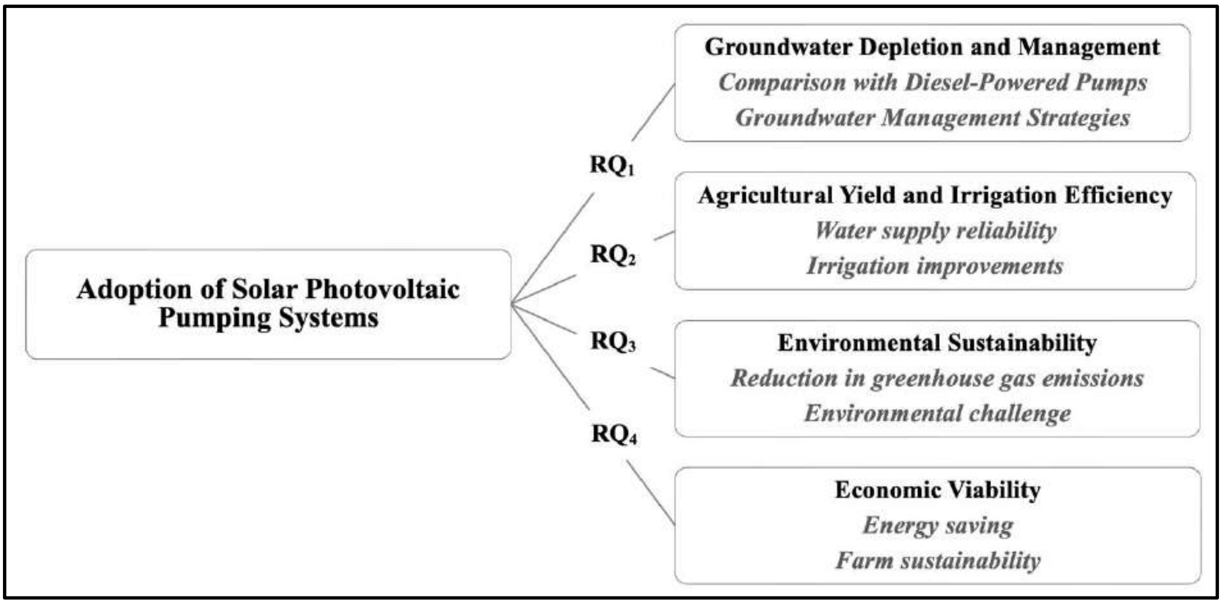
This study explores the relationship between the adoption of solar energy pumping systems and key outcomes related to groundwater management, agricultural productivity, environmental sustainability, and economic viability. A qualitative approach was adopted, utilizing thematic analysis to derive insights from the interviews with orchard managers. The study relies on a conceptual framework to guide the investigation and address the research questions posed earlier. **The** study evaluates the financial aspects of adopting solar energy, including initial investment costs, long-term savings, and economic sustainability.

Figure 1, presents the conceptual framework, positioning solar energy systems as the independent variable, influencing multiple dimensions of sustainability and economic performance. The four dependent variables examined are:

- ***Groundwater Depletion and Management :*** The study examines the impact of solar energy pumping systems on groundwater levels, especially compared to diesel-powered systems. Strategies for sustainable water management are also explored.
- ***Agricultural Yield and Irrigation Efficiency*** : The focus is on how solar PV systems influence agricultural productivity, irrigation reliability, and water-use efficiency.
- ***Environmental Sustainability*** : The research analyzes the environmental effects of solar-powered systems, particularly in reducing the carbon footprint and evaluating challenges related to their adoption.

- ***Economic Viability and Cost-Benefit Analysis*** The study evaluates the financial aspects of adopting solar energy, including initial investment costs, long-term savings, and economic sustainability.

Figure 1: Conceptual Framework



Source: Authors

The conceptual framework provides a holistic understanding of how solar photovoltaic systems in Moroccan orchards affect these interconnected variables, offering insights into the socio-economic and environmental dynamics at play.

4.3. Data processing

As outlined in Section **4.1**, the data collection process involved semi-structured interviews guided by a carefully designed protocol. Interviews, lasting 60 to 80 minutes, were conducted with orchard managers across varying farm sizes. All interviews were audio recorded and manually transcribed to ensure data accuracy. This allowed for the capture of essential nuances in responses, enhancing the robustness of the analysis. The data were analyzed using thematic analysis, employing both vertical and horizontal approaches. Vertical analysis explored individual interviews in depth, capturing unique insights, while horizontal analysis allowed for cross-interview comparisons to identify recurring themes. This dual analytical approach enabled a comprehensive understanding of the experiences of orchard managers.

5. Results and Discussion

5.1. Empirical Findings

This section presents the empirical findings of the study, with a focus on assessing the impact of solar photovoltaic pumping systems on groundwater management, agricultural yield, environmental sustainability, economic viability, and adoption prospects among the 15 Moroccan orchards interviewed in the Marrakesh region.

- **Theme 1: Groundwater Depletion and Management**

Observations on Groundwater Levels

The implementation of solar energy pumping systems among the studied farms revealed varied impacts on groundwater levels. The data indicates a clear stratification based on farm size:

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- *Stable Groundwater Levels:* A minority of the total farms (20%) reported stable groundwater levels after adopting solar energy pumping systems. This group included 60% of the small farms and 40% of the medium-sized farms. "We've noticed no significant changes in our groundwater levels since the shift to solar pumps" (interviewee n°1). The stability in these cases suggests that the adoption of solar energy may not significantly impact groundwater levels, potentially due to lower water usage or more efficient irrigation practices in these smaller and medium-sized operations.
- *Moderate Decline in Groundwater Levels:* Approximately 30% of the total farms (40% of small farms and 60% of medium-sized farms) observed a moderate decline in groundwater levels. "There's been a slight but noticeable drop in our water table, but nothing alarming" (R8). This observation suggests that while solar energy pumping systems have not led to drastic depletion, there is a noticeable impact on groundwater levels. The moderate decline could be attributed to increased water extraction facilitated by the reliable and abundant energy provided by solar systems.
- *Significant Decline in Groundwater Levels:* Notably, 50% of the total farms, including all large farms and two medium-sized farms, reported a substantial decline in groundwater levels. "Since we started using the solar pumps, we've been able to pump more water, which has unfortunately lowered our groundwater significantly" (interviewee n°11). This trend indicates that larger farms are more prone to groundwater over-extraction when using solar-powered irrigation systems, highlighting a potential risk of accelerated groundwater depletion in large-scale agricultural operations with higher water demands, reinforcing concerns about the environmental impact of large-scale solar irrigation.

Comparison with Diesel-Powered Pumps

The comparative analysis between solar-powered and diesel-powered pumps uncovered distinct performance patterns: consistent performance during peak sunlight hours and instability outside peak sunlight hours.

- *Consistent Performance During Peak Sunlight Hours:* Farm businesses reported that the performance of solar pumps was comparable to that of diesel-powered pumps during peak sunlight hours. "The solar pumps work just as well as the diesel ones when the sun is strong" (interviewee n°9). This similarity suggests that solar energy can be an effective alternative to diesel under optimal conditions, supporting the potential for broader adoption of solar technologies in agricultural practices.
- *Instability Outside Peak Sunlight Hours:* However, the performance of solar pumps became unstable outside of peak sunlight hours. "We struggle with water supply early in the morning and late in the evening, which affects our irrigation schedule" (interviewee n°14). This observation underscores the limitations of relying solely on solar energy and suggests the need for hybrid energy systems or advanced storage solutions to ensure a stable energy supply throughout the day.

Groundwater Management Strategies

The adoption of solar energy systems has led to varied approaches to groundwater management across different farm sizes.

- *Large Farms:* Large Farms have implemented precision irrigation systems, such as drip irrigation coupled with automated sensors, to manage groundwater more sustainably. "We've invested in advanced irrigation technologies that allow us to use water more efficiently, preserving our groundwater for the future" (interviewee n°12). This proactive approach reflects a commitment to optimizing water use and minimizing waste, which is critical for maintaining agricultural productivity while conserving groundwater resources.

- *Small and Medium-Sized Farms*: In contrast, small and medium-sized farms have not adopted specific strategies to manage groundwater more sustainably. “It's tough for us to invest in expensive systems like our larger counterparts” (interviewee n°2). This gap in sustainable practices may be due to limited access to resources or financial constraints, highlighting the need for targeted support to encourage broader adoption of efficient irrigation technologies across all farm sizes.

- **Theme 2: Agricultural Yield and Irrigation Efficiency**

Reliability of Water Supply

The adoption of solar PV systems among the surveyed farms has demonstrated consistent reliability in water supply. Managers across different farm sizes reported no significant changes in water supply reliability after installing solar PV systems, indicating that these systems effectively sustain irrigation needs previously met by conventional energy sources. “Switching to solar hasn't changed our water delivery schedules; it's as reliable as it was with diesel pumps” (interviewee n°10). This stability suggests that solar energy can seamlessly replace traditional energy sources without disrupting agricultural productivity. However, despite this stability, there has not been a corresponding increase in crop yields. “We haven't seen any real improvement in yields, just stable production with lower energy costs” (interviewee n°15). This observation implies that the primary benefit of solar PV systems may be energy sustainability rather than enhancing agricultural output. It also highlights the potential need for integrated advancements in irrigation efficiency or water management to fully leverage the benefits of solar technology in agriculture.

Impact on Crop Yields

The analysis of crop yield data revealed that the installation of solar PV systems did not lead to significant changes in agricultural productivity. Managers across the board reported unchanged crop yields post-installation, attributing this to the adequacy of their previous energy sources in meeting irrigation demands. “Our yields have stayed the same; the solar system does its job well, but it hasn't boosted our production” (interviewee n°5). This suggests that while solar energy is a viable and sustainable alternative, its impact on crop yields may be limited in contexts where irrigation needs were already adequately met by existing energy sources. Furthermore, the consistency in agricultural output observed suggests that while solar PV systems are capable of maintaining existing levels of productivity, they might not enhance yields without concurrent improvements in irrigation practices or agricultural techniques. “To really see a difference, we'd need to upgrade our irrigation methods alongside implementing solar” (interviewee n°6).

Changes in Irrigation Practices

The survey revealed no significant changes in irrigation practices following the adoption of solar energy. Farm businesses indicated that their irrigation methods remained consistent with those employed before the installation of solar PV systems, with no substantial improvements reported. “We've basically swapped out the energy source; our actual watering hasn't changed” (interviewee n°7). This continuity suggests that the transition to solar energy primarily substituted the energy source without altering water application methods. The benefits of solar energy in this context appear to be more related to cost savings rather than direct improvements in irrigation efficiency.

Irrigation Duration and Scheduling

The adoption of solar PV systems has influenced irrigation practices across the farm businesses. Smaller farms and 30% of medium-sized farms reported increasing their irrigation hours, while

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large farms and 70% of medium-sized farms maintained their peak-season schedules but extended irrigation during the off-season to fill reservoirs. “We're using the extra energy to boost our water reserves when the sun's out” (interviewee n°12). This flexibility, particularly in off-peak periods, underscores the strategic use of solar energy to enhance water security. Large farms, in particular, have adapted their schedules to maximize water storage, ensuring sufficient availability during high-demand periods. The variations in irrigation practices across farm sizes demonstrate the adaptability of solar PV systems to different operational needs.

Changes in Pump Power

The scalability of solar energy systems has allowed many farmers to enhance their irrigation capabilities. Among the farms, 60% increased pump power by adding more solar panels, while 40% maintained their existing power settings. “Adding more panels let us pump more water without higher costs” (interviewee n°8). This enhancement enables farm businesses to effectively meet rising irrigation demands. For those maintaining the same pump power, it suggests that their current systems were adequate or that economic constraints limited further expansion.

Irrigation Start and Stop Times

The adoption of solar energy has notably reshaped irrigation practices on the studied farms. On smaller farms and approximately half of the medium-sized farms, irrigation typically begins at sunrise and concludes at sunset, mirroring the operational hours of solar pumps. Larger farms, as well as the remaining medium-sized farms, similarly start irrigation at sunrise and extend these activities until sunset, often continuing beyond immediate requirements to replenish water reservoirs. “Our irrigation schedule now closely follows the sun” (interviewee n°5). This reliance on solar energy directly influences irrigation schedules, tying them closely to the availability of sunlight. While this approach underscores the environmental sustainability of solar-powered systems, it also necessitates strategic planning to optimize water storage capacities. The extended irrigation periods observed on larger farms, aimed at reservoir filling, reflect a proactive strategy to secure water resources for future use, thereby enhancing resilience against potential periods of reduced sunlight or increased water demand.

Storage Capacity Adjustments

The transition to solar PV systems has led large farms to increase their water storage capacity, aligning with the enhanced pump power provided by solar energy. In contrast, small and medium-sized farms reported no changes. “We've expanded our storage to make the most of our solar investment” (interviewee n°11). This expansion among large farms reflects a strategic approach to water management, leveraging the increased pumping capacity to secure resources for peak demand periods. The lack of change among smaller farms may indicate either sufficiency in existing storage or limitations in resources for additional infrastructure.

Economic Impact on Production Costs

The economic analysis revealed substantial cost savings across all farm sizes following the adoption of solar PV systems. Prior to installation, energy costs accounted for 25% to 30% of total production expenses. Post-installation, small farms and half of the medium-sized farms achieved complete elimination of energy costs, while large farms reduced these costs by 50%. “Solar has cut our energy bills in half” (interviewee n°14). These significant savings highlight the financial viability of solar energy, especially for smaller operations. The variation in savings among medium and large farms reflects differences in water resource availability and energy demands, indicating that the economic impact of solar PV systems is influenced by local conditions and operational scale.

- **Theme 3: Environmental Sustainability**

Environmental Benefits of Solar-Powered Irrigation

The transition to solar-powered irrigation systems has brought significant environmental benefits, particularly by reducing reliance on fossil fuels. Approximately 35% of large farms reported a reduction in fossil fuel usage since adopting these systems, directly contributing to lower greenhouse gas (GHG) emissions and aligning with climate change mitigation goals. “Switching to solar has allowed us to cut back significantly on diesel, reducing our carbon output” (interviewee n°12). This shift reduces the carbon footprint and promotes sustainable agricultural practices. However, this benefit was reported by only a subset of large farms, indicating variability in the effectiveness or implementation of solar energy across different operations. The reduction in fossil fuel usage underscores the potential of solar energy to advance broader sustainability goals within the agricultural sector.

Reductions in Greenhouse Gas Emissions and Other Environmental Improvements

The primary environmental benefit reported by farmers was the reduction in GHG emissions, attributed mainly to the decreased use of fossil fuels. “We've seen a noticeable drop in our greenhouse gas emissions since we started using solar pumps” (interviewee n°11). No other environmental improvements, such as enhanced air quality or reduced soil degradation, were noted. This emphasis on GHG reductions highlights the direct environmental impact of decreased fossil fuel consumption, but the absence of additional reported benefits suggests a potential lack of awareness or monitoring of the broader environmental impacts of solar-powered irrigation. These findings indicate a need for more comprehensive environmental assessments and awareness programs to help farmers recognize and leverage the full range of benefits associated with solar energy.

Environmental Challenges and Drawbacks

The implementation of solar-powered irrigation systems has led to environmental challenges due to the substantial land required for solar panel installations, often resulting in the removal of trees. “The space needed for solar panels has forced us to clear some wooded areas, which is a tough trade-off” (interviewee n°9). This issue is particularly problematic for small and medium-sized farmers who have limited land, making it more difficult to accommodate the necessary solar infrastructure without significant environmental trade-offs. The resulting deforestation undermines environmental benefits by reducing carbon sequestration, harming biodiversity, and destabilizing ecosystems.

- **Theme 4: Economic Viability and Cost-Benefit Analysis**

Initial Investment Costs

The transition to solar energy pumping systems requires a significant initial investment, presenting a substantial financial barrier for farmers. Reported costs for switching to solar energy range between 8,000 and 10,000 MAD per kilowatt peak (KWc), encompassing the purchase of solar panels, installation, maintenance, and integration with existing irrigation systems. “The upfront costs are quite high, but we view it as an investment into our farm’s future” (interviewee n°9). This variability in costs reflects the specific requirements of each farm, such as system size and technology quality. Despite the high upfront costs, farm businesses are motivated by the potential long-term financial benefits, particularly given the rising costs of conventional energy sources. “The decision to switch was tough, especially with the initial expense, but necessary to counter rising diesel prices” (interviewee n°14). This period has also witnessed a marked surge in the adoption of solar PV systems, as farm businesses seek to mitigate the economic impact of escalating energy prices.

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Long-Term Savings on Energy Costs

The adoption of solar energy systems offers significant long-term financial benefits, making the initial investment worthwhile. Managers reported that after an amortization period of 3.5 to 5 years, solar energy systems effectively become cost-free. “It takes a few years, but eventually, the savings on energy costs become substantial” (interviewee n°5). The high initial investment is offset by the absence of fuel costs or reduced reliance on grid electricity, leading to considerable savings. “Once we hit the break-even point, it's all savings from there” (interviewee n°7). The predictability and stability of solar energy costs enhance its appeal as a sustainable and economically viable option over time. However, the variation in amortization periods indicates that the rate at which these savings are realized depends on factors such as energy consumption patterns, system efficiency, and maintenance costs.

Impact on Economic Sustainability

The transition to solar energy is perceived as a positive contributor to the economic sustainability of the studied farms. Managers view it as economically viable once the initial investment is amortized, leading to significantly reduced energy costs. “Solar has really changed the game for us by decreasing our dependency on fluctuating fossil fuel prices” (interviewee n°11). By decreasing reliance on expensive fossil fuels and mitigating risks associated with energy price fluctuations, solar energy enhances the financial stability of farming operations. “After the solar energy system is paid off, ongoing costs are minimal, allowing us to invest more in other areas of the farm” (interviewee n°12). This is particularly relevant in the agri-sector, where energy costs represent a significant portion of operational expenses.

- **Theme 5: Adoption and Future Prospects**

Motivations for Adopting Solar Energy Pumping Systems

The primary motivation for adopting solar energy pumping systems was the need to mitigate rising energy costs, particularly in the wake of the COVID-19 pandemic. Managers identified the significant increase in energy prices as a key driver, prompting the shift toward more cost-effective and sustainable solutions. “Diesel prices skyrocketed after the pandemic, and we had to find an alternative to keep costs down” (interviewee n°14). Solar energy has emerged as a viable alternative, offering the potential to stabilize and reduce long-term energy expenditures amidst the volatility of conventional energy sources like diesel and electricity. This transition reflects a broader trend in agriculture toward renewable energy adoption to mitigate economic risks and enhance operational sustainability.

Barriers to Adoption and Solutions

All studied farm businesses faced significant barriers during the adoption of PV solar energy systems, including installation challenges, counterfeit or second-hand solar panels, technical issues, and a lack of professionalism among installers. “We had issues with poorly installed panels and even ended up with some second-hand ones that weren’t what we paid for” (interviewee n°7). The prevalence of counterfeit or second-hand panels highlights the need for stronger market regulation and quality control. Additionally, technical problems and unprofessional behavior from installers reveal gaps in reliable service provision, potentially deterring other farmers from adopting solar technology. “The installation process was a headache; the installers were not as experienced as they claimed” (interviewee n°3). Addressing these barriers is crucial for promoting wider adoption of solar energy in agriculture.

Future Plans for Solar Energy Use

Orchard managers expressed intentions to expand their solar energy systems to further reduce operational costs. "We plan to add more panels to increase our energy savings and possibly even power other parts of the farm" (interviewee n°11). This planned expansion reflects their view of solar technology as a long-term solution for minimizing energy expenses and insulating their operations from the volatility of conventional energy markets. The pace of expansion will depend on the availability of financial resources and opportunities, indicating that continued investment in solar energy infrastructure is contingent on external support or favorable economic conditions.

Support and Incentives for Wider Adoption

Farmers have emphasized the need for stronger financial support and incentives to promote the adoption of solar technology across farms of all sizes. "The subsidies we get don't cover enough of the costs, especially for smaller farms like ours" (interviewee n°2). A new subsidy program introduced in February 2024 offers a 30% subsidy on the cost of acquiring and installing solar pumping systems for farms with less than 10 hectares, capped at 3,000 MAD per hectare irrigated, 3,000 MAD per kilowatt-peak installed, and 30,000 MAD per project. However, farms exceeding 10 hectares are excluded from this support, and even small farms find the subsidy insufficient. "It's a start, but for larger farms, we don't qualify for any of these incentives, which makes expanding difficult" (interviewee n°12).

5.2. Discussion and Implications

This section discusses the implications of the empirical findings, linking them to broader theoretical frameworks and existing literature, and providing insights into the potential policy and practical applications necessary to enhance the sustainability and economic resilience of solar energy adoption in agriculture.

- **Theme 1: Groundwater Depletion and Management**

The empirical findings reveal that smaller farms generally maintain stable groundwater levels, suggesting that solar energy adoption may not significantly exacerbate groundwater depletion in low-demand scenarios. Larger farms experience a substantial decline in groundwater levels, indicating a risk of over-extraction when solar energy removes energy constraints on water use. This points to the need for careful consideration of scale when implementing solar-powered irrigation to avoid accelerating groundwater depletion. The comparison between solar and diesel-powered pumps highlights solar energy's potential to replace traditional energy sources under optimal conditions, with similar performance during peak sunlight hours. The instability of solar pumps outside these hours underscores the necessity for hybrid systems or advanced storage solutions to ensure a reliable water supply, especially in critical agricultural regions. Additionally, the divergent groundwater management practices among farms of different sizes emphasize the importance of resource access in adopting sustainable practices. Large farms' use of precision irrigation contrasts with the lack of such strategies among smaller operations, revealing a gap that must be addressed through targeted interventions. This suggests that while solar energy offers a path toward sustainability, its success depends on integrating it with robust groundwater management strategies, particularly in larger agricultural operations, to mitigate potential environmental risks.

- **Theme 2: Agricultural Yield and Irrigation Efficiency**

The reliability of water supply, maintained consistently post-installation, underscores the effectiveness of solar PV systems in replacing conventional energy sources without compromising irrigation needs. However, the absence of significant improvements in crop yields suggests that while solar energy offers a sustainable alternative, its contribution to agricultural productivity may be limited in scenarios where previous energy sources sufficiently

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met irrigation demands. This points to the necessity of integrating solar energy with advancements in irrigation practices to unlock potential yield benefits. The stability in irrigation practices following the adoption of solar PV systems further highlights the role of these systems as energy substitutes rather than as catalysts for improved agricultural methods. The unchanged irrigation methods across most farms suggest that the primary advantage of solar energy lies in cost savings rather than in direct enhancements of water use efficiency. Nonetheless, the extended irrigation hours on smaller and medium-sized farms, along with the increased pump power on 60% of the farms, indicate that solar energy has enabled some degree of operational flexibility. This adaptability is particularly evident in large farms, where increased storage capacities and strategic irrigation scheduling reflect a proactive approach to maximizing water security, especially during off-peak periods. Economic analysis reinforces the financial viability of solar PV systems, with substantial cost savings observed across all farm sizes. The complete elimination of energy costs for small farms and significant reductions for large farms emphasize the potential of solar energy to enhance economic sustainability, especially for smaller operations with limited resources. The variation in economic benefits, influenced by farm size and local conditions, underscores the importance of contextual factors in determining the full impact of solar energy adoption. Overall, the findings suggest that while solar PV systems are effective in sustaining irrigation needs and reducing production costs, their impact on agricultural productivity and water management practices may be constrained without further innovations in irrigation techniques and resource management.

- **Theme 3: Environmental Sustainability**

Solar-powered irrigation systems in the agricultural sector have proven effective in reducing fossil fuel dependency, thereby lowering greenhouse gas emissions and contributing to climate change mitigation efforts. This reduction in carbon footprint represents a significant step toward promoting sustainable agricultural practices. Yet, the variability in the reported benefits, particularly among small and medium-sized farms, suggests that the transition to solar energy is not uniformly effective. This inconsistency points to potential barriers in the implementation or scaling of these systems across different farm sizes. Moreover, while the reduction in GHG emissions is a notable achievement, the absence of additional reported environmental benefits, such as improved air quality or reduced soil degradation, raises concerns about the comprehensive understanding of solar energy's potential. This limited recognition of broader environmental impacts may be due to a lack of awareness or monitoring among farmers, which underscores the necessity for more thorough environmental assessments. Encouraging a holistic approach to evaluating the environmental effects of solar-powered irrigation could help farmers better appreciate and utilize the full spectrum of benefits. The discussion also reveals significant challenges associated with the widespread adoption of solar-powered irrigation systems, particularly concerning land use. The requirement for substantial land to install solar panels has led to environmental trade-offs, including deforestation and loss of biodiversity, especially among small and medium-sized farms. These challenges highlight the need for more sustainable and land-efficient solutions to integrate solar energy into agricultural practices without compromising environmental integrity.

- **Theme 4: Economic Viability and Cost-Benefit Analysis**

The initial investment required for transitioning to solar energy presents a substantial financial challenge, particularly for farmers with limited capital resources. Yet, the high upfront costs are counterbalanced by considerable long-term financial benefits, notably the substantial reduction in energy costs post-amortization. The adoption of solar energy systems, which typically become cost-neutral within 3.5 to 5 years, underscores the economic rationale for this transition, especially in light of escalating conventional energy prices since the COVID-19 pandemic. This period has seen a marked increase in the adoption of solar PV systems, as farmers seek to mitigate the financial strain caused by rising energy costs. The transition to solar energy not only reduces dependence on expensive fossil fuels but also enhances the economic sustainability of farming operations by stabilizing energy costs. This stability is particularly critical in the agriculture sector, where energy represents a significant portion of operational expenses. The long-term economic benefits, such as reduced operational costs and increased financial resilience, underscore the potential of solar energy to contribute to the overall sustainability of agricultural practices. Once the initial investment is amortized, the ongoing costs associated with solar energy systems are minimal, allowing farmers to allocate resources more efficiently and invest in further sustainability measures.

- **Theme 5: Adoption and Future Prospects**

The adoption of solar energy systems was primarily driven by the necessity to mitigate rising energy costs, a challenge exacerbated by the COVID-19 pandemic. This shift towards renewable energy is reflective of a broader trend in agriculture, where the need to stabilize long-term energy expenditures has become increasingly vital. Nonetheless, despite the clear economic motivations, significant barriers have impeded the widespread adoption of this technology. Challenges such as installation difficulties, the prevalence of counterfeit or second-hand panels, and a lack of professionalism among installers underscore the critical need for stronger market regulation and enhanced service reliability. These barriers present substantial risks, potentially dissuading other farms from transitioning to solar energy and thereby limiting the broader sustainability benefits that could be achieved. Moreover, while the intention to expand solar energy use is evident among orchard managers, the realization of these plans is contingent upon the availability of financial resources and supportive economic conditions. This reliance on external factors highlights the vulnerability of the agricultural sector in its pursuit of energy sustainability, particularly in the context of fluctuating conventional energy markets.

6. Conclusion

This study assessed the impact of solar photovoltaic pumping systems on groundwater conservation, agricultural sustainability, and economic viability in Moroccan arboriculture, guided by four key research questions. The findings closely align with existing theoretical frameworks and empirical studies. While solar PV systems reduce the energy intensity of water pumping, they may still contribute to groundwater over-extraction, especially on larger farms. This observation is consistent with prior studies indicating similar risks associated with solar PV adoption (Chel & Kaushik, 2011; Chilundo et al., 2019). The reliable energy supply from solar PV systems can inadvertently encourage increased water usage, reflecting patterns observed with diesel-powered pumps (Foster & Cota, 2014). Regarding agricultural yields, the adoption of solar PV systems has maintained water supply reliability, with no significant changes in yield post-adoption. This supports existing literature on the reliability of solar energy in maintaining crop health (Kelley et al., 2010; Narale et al., 2013). However, the anticipated increase in productivity was not realized, suggesting that efficiency gains from solar PV systems do not necessarily translate into higher agricultural output unless accompanied by advanced irrigation techniques (Verma et al., 2021). The environmental benefits of solar PV systems, such as reduced greenhouse gas emissions and a lower carbon footprint, are consistent with the literature (Chel & Kaushik, 2011; Das & Mandal, 2018). Economically, solar PV systems have proven beneficial, particularly for small and medium-sized farms, with significant reductions in energy costs, and in some cases, the complete elimination of these costs after the amortization period. This underscores the financial viability of solar PV systems for Moroccan farmers (Abousserhane et al., 2022; Narale et al., 2013). The reduced dependency on fossil fuels further supports the transition towards more sustainable and resilient agricultural practices (Foster & Cota, 2014). The study emphasizes the importance of targeted policy interventions and support mechanisms to facilitate the sustainable integration of solar energy in agriculture. To fully harness the potential of solar energy in this sector, comprehensive strategies are necessary. These include appropriate sizing of PV systems, coupling PV with low-pressure irrigation and ICT solutions, and making subsidies conditional on improved irrigation management (Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH, 2019). Governance measures should enforce water extraction limits, install meters, and restrict the expansion of irrigated areas. Subsidies should target farms under 5 hectares, with preferential rates for collective systems, to prevent groundwater overexploitation. Additionally, rigorous control mechanisms, such as equipment certification and post-installation validation, are essential. These findings underscore the need for comprehensive strategies and continued support for solar energy adoption to maximize benefits and ensure sustainable agricultural development in semi-arid regions like Morocco. The insights gained from this study provide valuable guidance for policymakers and stakeholders in promoting sustainable and economically viable agricultural practices.

References

(1). Abousserhane, Z., Abbou, A., & Bouzakri, H. (2022). Effective power management of PV/battery hybrid system under varying frequency modes. In *2022 2nd International Conference on Innovative Research in Applied Science, Engineering and Technology (IRASET)* (pp. 1-8). Meknes, Morocco. https://doi.org/10.1109/IRASET52964.2022.9738417

(2). Armanuos, A. M., Negm, A., & Tahan, A. H. M. H. E. (2016). Life Cycle Assessment of Diesel Fuel and Solar Pumps in Operation Stage for Rice Cultivation in Tanta, Nile Delta, Egypt. *Procedia Technology*, *22*, 478-485. https://doi.org/10.1016/j.protcy.2016.01.062

(3). Bentaleb, F. Z., & Taki, M. (2023a). Operational impact of information system integration on cost efficiency, inventory control, and timeliness in citrus supply chain dynamics. *International Journal of Accounting, Finance, Auditing, Management and Economics*, *4*(6-2), 671-687. https://doi.org/10.5281/zenodo.10440323

(4). Bentaleb, F. Z., & Taki, M. (2023b). Information system integration in citrus packing stations: A key driver for product quality and customer satisfaction. *Revue Internationale des Sciences de Gestion*, *6*(4), 654-677. https://doi.org/10.5281/zenodo.10031498

(5). Bentaleb, F. Z., & Taki, M. (2023c). ERP-mediated information integration: An empirical case study on supply chain efficiency in Morocco's red meat sector. *Revue Internationale des Sciences de Gestion*, *6*(4), 635–653. https://doi.org/10.5281/zenodo.10031496

(6). Bentaleb, F. Z., & Taki, M. (2024a). The multidimensional impact of information system integration on SCM: Evidence from citrus packing stations in Morocco. In *2024 IEEE 15th International Colloquium on Logistics and Supply Chain Management (LOGISTIQUA)* (pp. 1-6). IEEE. https://doi.org/10.1109/LOGISTIQUA61063.2024.10571483

(7). Bentaleb, F. Z., & Taki, M. (2024b). Sustainable practices in Moroccan citrus farming: A case study on agri-food supply chains. In *2024 IEEE 15th International Colloquium* *on Logistics and Supply Chain Management (LOGISTIQUA*) (pp. 1-6). https://doi.org/10.1109/LOGISTIQUA61063.2024.10571372

(8). Bhatta, T. (2018). Case study research, philosophical position and theory building: A methodological discussion. *Dhaulagiri Journal of Sociology and Anthropology*, *12*, 72-79. https://doi.org/10.3126/dsaj.v12i0.22182

(9). Chandel, S. S., Naik, M. N., & Chandel, R. (2015). 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

(10). Chel, A., & Kaushik, G. (2011). Renewable energy for sustainable agriculture. *Agronomy for Sustainable Development*, *31*(1), 91-118. https://doi.org/10.1051/agro/2010029

(11). Chen, S., Chen, X., & Xu, J. (2016). Impacts of climate change on agriculture: Evidence from China. *Journal of Environmental Economics and Management*, *76*, 105-124. https://doi.org/10.1016/j.jeem.2015.01.005

(12). Chilundo, R. J., Maúre, G. A., & Mahanjane, U. S. (2019). Dynamic mathematical model design of photovoltaic water pumping systems for horticultural crops irrigation: A guide to electrical energy potential assessment for increasing access to electrical energy. *Journal of Cleaner Production*, *238*, 117878. https://doi.org/10.1016/j.jclepro.2019.117878

(13). Das, M., & Mandal, R. (2018). A comparative performance analysis of direct, with battery, supercapacitor, and battery-supercapacitor enabled photovoltaic water pumping systems using centrifugal pump. Solar *Energy*, *171*, 302-309. https://doi.org/10.1016/j.solener.2018.06.069

(14). Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. (2019). *Investigation de l'impact des installations de pompage solaire sur la consommation d'eau et la situation socio-économique d'un agriculteur dans 3 zones pilotes au Maroc.* Programme d'Appui à la Gestion Intégrée des Ressources en Eau (AGIRE). https://uploads.water-energy-food.org/legacy/pompage_solaire_1.1.pdf

(15). Ebneyamini, S., & Sadeghi Moghadam, M. R. (2018). Toward Developing a Framework for Conducting Case Study Research. *International Journal of Qualitative Methods*, *17*(1), 1609406918817954. https://doi.org/10.1177/1609406918817954

(16). Elhami, A., & Khoshnevisan, B. (2022). Conducting an interview in qualitative research: The modus operandi. *MEXTESOL Journal*, *46*(1), 1-7. https://doi.org/10.61871/mj.v46n1-3

(17). El-Nashar, W., & Elyamany, A. (2023). Win–win strategies for transboundary water management during the GERD operating stage. *Water Resources Management*, *37*, 915–936. https://doi.org/10.1007/s11269-022-03413-9

(18). Elshall, A. S., Arik, A. D., El-Kadi, A. I., Pierce, S., Ye, M., Burnett, K. M., Wada, C. A., Bremer, L. L., & Chun, G. (2020). Groundwater sustainability: A review of the interactions between science and policy. *Environmental Research Letters*, *15*(9), 1-57. https://doi.org/10.1088/1748-9326/ab8e8c

(19). Eltamaly, A. M., & Mohamed, M. A. (2016). A novel software for design and optimization of hybrid power systems. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *38*(4), 1299-1315. https://doi.org/10.1007/s40430-015-0363-z

(20). FAO (Food and Agriculture Organization of the United Nations). (2011). *Save and Grow: A Policymaker's Guide to the Sustainable Intensification of Smallholder Crop Production.* FAO, Rome, Italy.

(21). Foster, R., & Cota, A. (2014). Solar water pumping advances and comparative economics. *Energy Procedia*, *57*, 1431-1436. https://doi.org/10.1016/j.egypro.2014.10.156

(22). Gallagher, T. L., & Gergel, S. E. (2017). Landscape indicators of groundwater nitrate concentrations: An approach for trans-border aquifer monitoring. *Ecosphere*, *8*(12), e02047. https://doi.org/10.1002/ecs2.2047

(23). Gautam, H. R., & Kumar, R. (2007). Need for rainwater harvesting in agriculture. *Journal of Kurukshetra*, *55*, 12-15.

(24). Hansen, C. B. (2007). Generalized least squares inference in panel and multilevel models with serial correlation and fixed effects. *Journal of Econometrics*, *140*(2), 670-694. https://doi.org/10.1016/j.jeconom.2006.07.011

(25). International Monetary Fund. (2017). *The Effects of Weather Shocks on Economic Activity. How Can Low-Income Countries Cope?* IMF Publication. Chapter 3.

(26). Juvancir da Silva, V., Fernandes, M., Limont, M., Dziedzic, M., Andreoli, C. V., & Rauen, W. B. (2020). Water sustainability assessment from the perspective of sustainable development capitals: Conceptual model and index based on literature review. *Journal of Environmental Management*, *254*, 109750. https://doi.org/10.1016/j.jenvman.2019.109750

(27). Kallio, H., Pietilä, A., Johnson, M., & Kangasniemi, M. (2016). Systematic methodological review: Developing a framework for a qualitative semi-structured interview guide. *Journal of Advanced Nursing*, *72*(12), 2954-2965. https://doi.org/10.1111/jan.13031

(28). Kalogiannidis, S., Kalfas, D., Paschalidou, M., & Chatzitheodoridis, F. (2024). Synergistic impacts of climate change and wildfires on agricultural sustainability—A Greek case study. *Climate*, *12*(9), 144. https://doi.org/10.3390/cli12090144

(29). Kelley, L. C., Gilbertson, E., Sheikh, A., Eppinger, S. D., & Dubowsky, S. (2010). On the feasibility of solar-powered irrigation. *Renewable and Sustainable Energy Reviews*, *14*(9), 2906-2915. https://doi.org/10.1016/j.rser.2010.06.006

(30). Kumar, S., & Kaur, T. (2016). Development of ANN Based Model for Solar Potential Assessment Using Various Meteorological Parameters. *Energy Procedia*, *90*, 587-592. https://doi.org/10.1016/j.egypro.2016.11.239

(31). Kunen, E., Pandey, B., Foster, R., Holthaus, J., Shrestha, B., & Ngetich, B. (2015). Solar water pumping: Kenya and Nepal market acceleration. In *ISES Conference Proceedings, Solar World Congress*, Daegu, Korea.

(32). Lai, D., & Roccu, R. (2019). Case study research and critical IR: the case for the extended case methodology. *International Relations*, *33*(1), 67-87. https://doi.org/10.1177/0047117818818243

(33). Lampridi, M. G., Sørensen, C. G., & Bochtis, D. (2019). Agricultural sustainability: A review of concepts and methods. *Sustainability*, *11*(18), 5120. https://doi.org/10.3390/su11185120

(34). Ma, W., & Rahut, D. B. (2024). Climate-smart agriculture: Adoption, impacts, and implications for sustainable development. *Mitigation and Adaptation Strategies for Global Change*, *29*(5), 44. https://doi.org/10.1007/s11027-024-10139-z

(35). Malla, G. (2009). Climate Change and Its Impact on Nepalese agriculture. *Journal of Agriculture and Environment*, *9*, 62-71. https://doi.org/10.3126/aej.v9i0.2119

(36). Mason, W., Morris, K., Webb, C., Daniels, B., Featherstone, B., Bywaters, P., Mirza, N., Hooper, J., Brady, G., Bunting, L., & Scourfield, J. (2020). Toward Full Integration of Quantitative and Qualitative Methods in Case Study Research: Insights From Investigating Child Welfare Inequalities. *Journal of Mixed Methods Research*, *14*(2), 164-183. https://doi.org/10.1177/1558689819857972

(37). Mendelsohn, R., Nordhaus, W. D., & Shaw, D. (1994). The impact of global warming on agriculture: a Ricardian analysis. *American Economic Review, 84*(4), 753–771.

(38). Narale, P. D., Rathore, N. S., & Kothari, S. (2013). Study of solar PV water pumping system for irrigation of horticulture crops. *International Journal of Engineering Science Invention, 2*(12), 54-60.

(39). NSW Farmers, & GSES. (2015). *Solar-powered pumping in agriculture: A guide to system selection and design. NSW Farmers.* Retrieved from https://www.eec.org.au/uploads/Sector%20Development/NSW%20Farmers%20-%20Solar-powered%20pumping%20in%20agriculture.pdf

(40). Onghena, P., Maes, B., & Heyvaert, M. (2019). Mixed Methods Single Case Research: State of the Art and Future Directions. *Journal of Mixed Methods Research, 13*(4), 461-480. https://doi.org/10.1177/1558689818789530

(41). Queirós, A., Faria, D., & Almeida, F. (2017). Strengths and limitation of qualitative and quantitative research methods. *European Journal of Education Studies, 3*(9), 369-387. https://doi.org/10.5281/zenodo.887089

(42). Roulston, K., & Choi, M. (2018). Qualitative interviews. In *U. Flick (Ed.), The SAGE handbook of qualitative data collection* (pp. 233-249). SAGE Publications. https://doi.org/10.4135/9781526416070

(43). Suojanen, S., Hakkarainen, E., Tähtinen, M., & Sihvonen, T. (2017). Modeling and analysis of process configurations for hybrid concentrated solar power and conventional steam power plants. *Energy Conversion and Management, 134*, 327-339. https://doi.org/10.1016/j.enconman.2016.12.048

(44). Swaminathan, M. S. (2010). An evergreen revolution. In *Science and Sustainable Food Security: Selected Papers of MS Swaminathan* (pp. 325-329).

(45). Tang, B., Meng, F., Dong, F., Zhang, H., & Meng, B. (2024). The spatiotemporal evolution of extreme climate indices in the Songnen Plain and its impact on maize yield. *Agronomy, 14*(9), 2128. https://doi.org/10.3390/agronomy14092128

(46). Tsakok, I. (2023). *Short of Water and Under Increasing Pressure to Deliver Food Security: Key Policy Considerations - The Case of the Kingdom of Morocco* (Policy Paper No. PP - 06/23). Policy Center for the New South. Retrieved from https://www.policycenter.ma/sites/default/files/2023-05/PP_06-23%20%28Tsakok%29_0.pdf

(47). United Nations. (2012). *Food and Agriculture : Sustainable Development*. Retrieved from https://sustainabledevelopment.un.org/topics/foodagriculture

(48). VanWynsberghe, R., & Khan, S. (2007). Redefining Case Study. *International Journal of Qualitative Methods, 6*(2), 80–94. https://doi.org/10.1177/160940690700600208

(49). Verma, S., Mishra, S., Chowdhury, S., Gaur, A., Mohapatra, S., Soni, A., & Verma, P. (2020). Solar PV powered water pumping system – A review. Materials Today: *Proceedings, 46*(11), 5601-5606. https://doi.org/10.1016/j.matpr.2020.09.434

(50). World Bank Group (WBG). (2017, November). *Managing Urban Water Scarcity in Morocco. Water Global Practice.* https://openknowledge.worldbank.org/bitstream/handle/10986/29190/122698-WP-P157650-Summary-Report-Urban-water-scarcity-in-Morocco-ENG-P157650-2017-12-25-04-12.pdf?sequence=1&isAllowed=y

(51). World Bank Group (WBG). (2021). *Morocco: Climate Risk Country Profile.* https://climateknowledgeportal.worldbank.org/sites/default/files/2021-09/15725-WB_Morocco%20Country%20Profile-WEB.pdf

(52). World Bank Group (WBG). (2022, October). *Morocco Country Climate and Development Report.*

ISSN: 2658-8455
Volume 5, Issue 10 (2024), pp. 88-109.

https://openknowledge.worldbank.org/bitstream/handle/10986/38240/Morocco_CCDR.pdf?sequence=13&isAllowed=y

(53). World Bank. (1980, May 02). *Memorandum on Morocco's Agricultural Sector: Identification of Issues and Bank Strategy* (Report No. 2667a-MOR). https://documents1.worldbank.org/curated/en/114101468280177392/pdf/multi-page.pdf

(54). Xu, J., Shrestha, A. B., Vaidya, R., Eriksson, M., & Hewitt, K. (2007). *The Melting Himalayas-Regional Challenges and Local Impacts of Climate Change on Mountain Ecosystems and Livelihoods.* ICIMOD Technical Paper. International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal.

(55). Zhou, D., & Abdullah. (2017). The acceptance of solar water pump technology among rural farmers of northern Pakistan: A structural equation model. *Cogent Food and Agriculture, 3*(1), 1280882. https://doi.org/10.1080/23311932.2017.1280882