

DIGITAL RENEWABLE-ENERGY INNOVATIONS FOR GROUNDWATER-SAFE SOLAR IRRIGATION IN A CLIMATE VULNERABLE CONTEXT - A CASE STUDY OF PUNJAB, PAKISTAN

INNOVATIONS NUMÉRIQUES EN MATIÈRE D'ÉNERGIES RENOUVELABLES POUR UNE IRRIGATION SOLAIRE PRÉSERVANT LES EAUX SOUTERRAINES DANS UN CONTEXTE DE VULNÉRABILITÉ CLIMATIQUE – ÉTUDE DE CAS DU PENDJAB, AU PAKISTAN

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ABSTRACT

Pakistan's agriculture sector faces an intensifying water-energy-climate crisis driven by groundwater depletion, rising energy costs, and climate variability. Solar-powered irrigation systems (SPIS) have emerged as a viable alternative to diesel- and electricity-powered tubewells, offering opportunities to reduce operational costs and greenhouse gas (GHG) emissions, while improving energy access in rural areas. However, unregulated adoption of solar irrigation may accelerate groundwater over-extraction, undermining long-term sustainability. This research develops a data-driven framework to promote sustainable solar irrigation in Punjab, Pakistan, by integrating two digital decision-support tools: Solar Suitability Mapping (SSM) and Solar Irrigation Pump Sizing Tool (SIP-ST). The research combines geospatial analysis, hydrological parameters, farm-level irrigation requirements, and socio-economic variables to identify optimal locations and configurations for solar irrigation systems. Findings reveal significant spatial variability in solar suitability across Punjab, with Southern districts including Rahim Yar Khan (R.Y. Khan), Okara, and Vehari exhibiting high potential due to favorable solar irradiance and groundwater conditions. Results demonstrate that optimized pump sizing can significantly reduce energy waste and prevent over-extraction of groundwater. The integration of these tools supports irrigation efficiency and aligns solar adoption with groundwater sustainability objectives. The research further highlights the importance of linking renewable energy transitions with water governance frameworks and high-efficiency irrigation systems (HEIS). The findings contribute to policy development by offering a scalable and evidence-based model for climate-resilient agriculture thereby supporting Pakistan's commitments to sustainable development goals (SDGs) and climate mitigation strategies.

Keywords: digital innovations; climate vulnerable context; agriculture sector; groundwater depletion; long-term sustainability.

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RÉSUMÉ

Le secteur agricole pakistanais est confronté à une crise croissante de l'eau, de l'énergie et du climat, alimentée par l'épuisement des eaux souterraines, la hausse des coûts énergétiques et la variabilité climatique. Les systèmes d'irrigation à énergie solaire (SPIS) se présentent comme une solution de remplacement viable aux puits tubulaires alimentés au diesel ou à l'électricité, offrant la possibilité de réduire les coûts d'exploitation et les émissions de gaz à effet de serre (GES), tout en améliorant l'accès à l'énergie dans les zones rurales. Cependant, l'adoption non réglementée de l'irrigation solaire peut accélérer la surexploitation des eaux souterraines et compromettre la durabilité à long terme. Cette recherche élabore un cadre fondé sur les données pour promouvoir une irrigation solaire durable au Pendjab, au Pakistan, en intégrant deux outils numériques d'aide à la décision : Solar Suitability Mapping (SSM) et Solar Irrigation Pump Sizing Tool (SIP-ST). La recherche combine l'analyse géospatiale, des paramètres hydrologiques, les besoins d'irrigation à l'échelle de l'exploitation et des variables socioéconomiques afin de déterminer les emplacements et les configurations optimaux des systèmes d'irrigation solaire. Les résultats révèlent une forte variabilité spatiale de l'aptitude à l'irrigation solaire au Pendjab, les districts du sud, notamment Rahim Yar Khan (R.Y. Khan), Okara et Vehari, présentant un fort potentiel grâce à un rayonnement solaire et à des conditions de nappe favorables. Les résultats montrent qu'un dimensionnement optimisé des pompes peut réduire sensiblement le gaspillage d'énergie et prévenir la surexploitation des eaux souterraines. L'intégration de ces outils améliore l'efficacité de l'irrigation et aligne l'adoption de l'énergie solaire sur les objectifs de durabilité des eaux souterraines. La recherche souligne en outre l'importance d'articuler la transition vers les énergies renouvelables avec les cadres de gouvernance de l'eau et les systèmes d'irrigation à haute efficacité (HEIS). Ces résultats contribuent à l'élaboration des politiques en proposant un modèle évolutif et fondé sur des données probantes pour une agriculture résiliente au climat, soutenant ainsi les engagements du Pakistan envers les objectifs de développement durable (ODD) et les stratégies d'atténuation du changement climatique.

Mots clés : Innovations numériques; Contexte de vulnérabilité climatique; Secteur agricole; Epuisement des eaux souterraines; Durabilité à long terme.

INTRODUCTION

Agriculture remains the backbone of Pakistan's economy, contributing substantially to national output and employment, while supporting food security for a rapidly growing population. The sector is heavily dependent on irrigation, with the Indus Basin Irrigation System (IBIS) providing the primary water supply for crop production. In conjunction with this phenomenon, the process of urbanization has not only led to a notable escalation in the requirement for domestic water supply, but has also resulted in a corresponding surge in industrial water consumption as a direct consequence of economic progress. However, increasing water scarcity, deteriorating infrastructure, and climate variability have significantly reduced the reliability of surface water resources. As a result, farmers have become increasingly dependent on groundwater extraction to meet irrigation demands.

Despite possessing an extensive irrigation infrastructure and the fourth-largest groundwater aquifer globally, it is deplorable that the circumstances have contributed to a decline in per capita water availability that has dipped below the critical threshold of 1,000 cubic meters (m^3) to 899 m^3 in 2025 (National Assembly of Pakistan, 2026). In contrast, it is imperative to highlight that Pakistan's existing water productivity ranks at the 8th percentile globally with a value of USD 1.38 per m^3 of water extracted from the Indus River Basin (IRB) and the Indus aquifer (Lytton et al., 2021). This comparison highlights a key imbalance, while total availability is shrinking, the economic return per unit of water remains disproportionately low. Therefore, it is imperative for the country to optimize the utilization of its water resources to enhance its value proposition, while overcoming the water-related challenges.

Declining groundwater tables impose negative environmental and economic externalities (e.g., increasing irrigation costs) and spatial externalities (e.g., excessive extraction from one tubewell can affect the pumping rate of a nearby well). Khan et al. (2016) suggested that groundwater extraction costs will increase by 270% over the next 20 years. However, there is a relative dearth of information about the magnitude of spatial impacts that some users have on others. Besides affecting groundwater levels, there is potential for social conflict among groundwater users in high-tubewell-density areas like Punjab. Since the 1960s Green Revolution, groundwater use in Punjab has increased from just 8% to more than 50% (Byerlee and Siddiq 1994; Nabeel 2021). In the sugarcane-

wheat zone, groundwater irrigation supports cropping intensities of 234% (Mirza and Latif 2012). Another important factor was the Indus Water Treaty which compromised 8 million cubic feet per second of surface water (Amir 2005).¹² The lack of improvements to surface water systems, unimpeded tubewell growth, a soaring population, and short-sighted groundwater policies contributed to significant increases in groundwater use in subsequent periods. Improving water productivity alone cannot solve Pakistan's water crisis, which is driven by inefficient water use, weak governance, deteriorating irrigation infrastructure, uncontrolled groundwater abstraction, and growing climate pressures. Significant losses across the Indus Basin Irrigation System reduce overall water-use efficiency, while declining surface water availability has increased reliance on groundwater, which now supplies more than 60% of irrigation needs, raising concerns about aquifer depletion and long-term sustainability (PCRWR, 2018; Shah and Akbar, 2021).

The absence of effective regulations on agricultural tubewell installation has accelerated groundwater extraction and expanded dependence on diesel- and electricity-powered irrigation. While these systems have supported agricultural growth, they have also contributed to aquifer depletion, rising energy costs, and increased greenhouse gas emissions. In response, solar-powered irrigation systems (SPIS) have emerged as a promising alternative, leveraging Pakistan's abundant solar resources to reduce irrigation costs, enhance energy security, and lower emissions. However, unregulated solarization may further intensify groundwater depletion by enabling unrestricted water extraction.

This research addresses the need to balance renewable energy adoption with sustainable groundwater management. Focusing on Punjab, it develops an integrated framework that combines solar irrigation planning with groundwater-sensitive decision-support tools to support evidence-based policymaking and sustainable agricultural development.

National Water Policy 2018

The enormous increase in tubewells and rapidly falling groundwater tables has challenged the conventional approach to groundwater use and management. In a new approach, the National Water Policy 2018 (NWP-18) focused on balancing groundwater recharge and abstraction. NWP-18 aims to provide the basis for more effective groundwater resources on a national level, using the information on groundwater quality and quantity to identify zones with different groundwater development potential at the canal, command, and subbasin levels and provide recommendations for installing different types of tubewells in the different zones with a focus on promoting solar-powered tubewells. Note that policy does not lead to management unless it is converted into legislation with clear, assigned responsibilities for specific ministries. However, any pathway to sustainable groundwater management must address critical gaps in the NWP-18. Currently, NWP-18 aims to improve knowledge of groundwater resources and identify and manage groundwater quality. The NWP-18 legal framework remains unclear about how to support groundwater management. Activities related to groundwater management are fragmented, and national, provincial, and local water institutions lack coordination for collecting and integrating groundwater data. Similarly, groundwater monitoring is scattered, and there is a dearth of reliable data on groundwater recharge rates, abstraction volumes, salinity, and even on groundwater quality parameters, which can hinder policy measures related to groundwater management (Lytton et al. 2020; Davies et al. 2021).

Punjab's most significant pieces of legislation for groundwater management are the Punjab Water Act 2019, Punjab Irrigation and Drainage Authority Act 1997, Punjab Local Government Act 2019, Punjab Environmental Protection Act 1997, Punjab Soil Reclamation Act 1952, and Punjab Canal and Drainage Act 1873. Following the repeal of the Punjab Irrigation and Drainage Authority Act 1997 and the Easement Act of 1882 in 2019, the conservation, allocation, and management of water resources in the province, including groundwater, is now the responsibility of the Punjab Water Resources Commission under the Punjab Water Act 2019. Although provincial water policy frameworks are being

¹² A unit of flow equal to one cubic foot per second.

developed in other provinces, Punjab led the way by approving the Punjab Water Policy in December 2018 and the Punjab Water Act in 2019.

Given the importance of groundwater, the Punjab Water Policy sets out explicit high-level objectives, emphasizing balancing recharge levels through regulation, reallocating canal allowances, inducing aquifer recharge, and monitoring groundwater levels for sustainable management. Since 2019, Punjab's Annual Development Programs have aimed to develop a holistic approach to achieving the objectives outlined in the policy by prioritizing sectoral strategies to optimize the efficiency of surface and groundwater use and to control groundwater mining. It allocates funding to induce groundwater recharge and to improve groundwater monitoring information through surveys, investigations, and research.

LITERATURE REVIEW

The observed behavioral pattern of individuals in relation to the utilization of groundwater resources is remarkably dynamic. Farmers possess limited knowledge of the potential negative implications of the haphazard, unpredictable nature of groundwater extraction, as their primary interest is to pump more water to meet rising crop water requirements. These tubewells have been found to make a significant and concerning contribution to the annual carbon dioxide (CO₂) emissions of approximately 5.02 million metric tons (FAO, 2024). The environmental costs of this groundwater dependence are becoming increasingly severe, as uncontrolled pumping leads to declining aquifer levels, accelerating salinity intrusion, and increasing GHG emissions.

In Punjab alone, the number of tubewells has increased from approximately 0.8 million in 2000 to over 1.4 million by 2020 (Figure 1) with more than 90% being privately owned and operated by farmers (PCRWR, 2021). In Southern Sindh and parts of Balochistan, excessive pumping has led to aquifer salinization, with over 70% of groundwater deemed unfit for irrigation or drinking due to high levels of total dissolved solids (TDS) and arsenic contamination (Shaikh, 2024). In the realm of electricity-powered tubewells, farmers face significant challenges due to load-shedding and the rising cost of electricity. However, diesel-powered tubewells represent an even larger concern, both economically and environmentally.

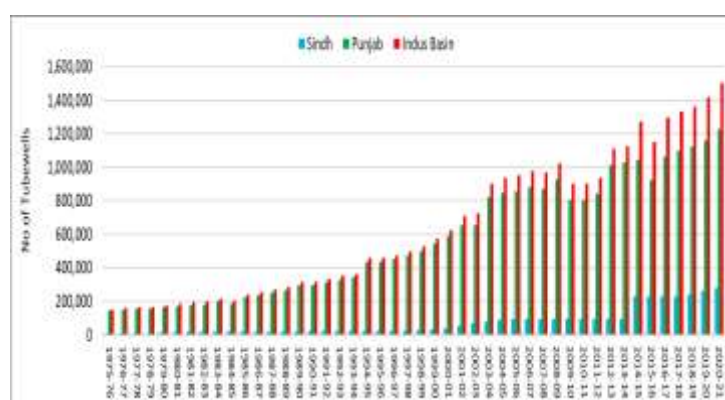


Figure 1: Tubewell Installation across Pakistan

This growing energy-water nexus highlights a vicious cycle: rising diesel costs erode farmers' profitability, while unregulated groundwater abstraction continues to accelerate hydrological imbalances in the water-stressed regions. Research highlights that if the trajectory continues, Pakistan could face a 31% water shortfall by the end of 2025 thereby severely undermining agricultural productivity and rural livelihoods (GoP 2018). Therefore, a strategic shift towards clean energy alternatives such as SPIS, alongside sustainable water governance reforms, is critical to avert an impending water-energy-agriculture crisis within the country's existing governance and political landscape.

Such unsustainable energy-water dynamics call for urgent policy interventions. On one hand, the financial vulnerability of smallholder farmers due to high fuel costs directly threatens their livelihoods and food security. On the other hand, the environmental footprint of diesel-powered pumping coupled with unregulated aquifer depletion jeopardizes long-term agricultural sustainability. These intertwined challenges underscore the need to transition to cleaner and cost-effective technologies such as SPIS alongside groundwater governance reforms to ensure regulated extraction and sustainable usage.

The transition to renewable energy is increasingly viewed as a key pathway for sustainable agriculture in water-stressed regions. Rising electricity costs and frequent power outages have accelerated interest in solar-powered irrigation systems (SPIS) as an alternative to diesel and electric tubewells. However, concerns remain that unregulated solarization could encourage excessive groundwater pumping and further aquifer depletion. Therefore, SPIS adoption must be integrated with groundwater governance measures and promoted alongside high-efficiency irrigation systems (HEIS) such as drip and sprinkler irrigation to ensure both economic viability and sustainable water use.

SPIS has gained global attention due to its potential to address the Water-Energy-Food (WEF) Nexus. These systems provide a clean and cost-effective alternative to conventional pumping technologies in regions with high solar potential and limited access to reliable electricity. In the context of solar irradiation, it has been approximated that Pakistan receives an average of approximately 3,000 hours of sunlight annually, which can produce 5-7 kilowatt hours per square meter (kWh/m²) of solar energy (Muhammad et al., 2017). These favorable solar irradiation levels make SPIS a strategically viable solution for addressing Pakistan's energy-water-climate interlinkages, if adoption is paired with regulations to manage groundwater abstraction sustainably. Upon successful completion of the installation process, SIPs operate exclusively on energy derived from renewable sources, thereby ensuring a complete absence of pollution and GHG emissions.

Solar-powered irrigation systems (SPIS) offer significant benefits by reducing energy costs, lowering emissions, and enhancing farmers' energy security. However, without effective regulation, lower pumping costs may encourage excessive groundwater extraction, accelerating aquifer depletion. In Punjab, rising water demand and widespread groundwater dependence have intensified concerns regarding groundwater sustainability. Recent studies highlight the need to integrate solar irrigation with groundwater governance, including groundwater monitoring, abstraction controls, and the promotion of HEIS. Digital decision-support tools further support sustainable planning by combining geospatial, hydrological, and socio-economic data to guide targeted investments and resource allocation.

While SPIS represent a transformative opportunity for sustainable agricultural development, challenges related to affordability, equitable access, and groundwater sustainability remain. This study addresses these challenges by developing an integrated framework that links spatial suitability assessment with farm-level system optimization to support evidence-based and groundwater-sensitive solar irrigation planning.

METHODOLOGY

The study adopts a mixed-methods approach combining geospatial analysis, hydrological modeling, and engineering-based calculations to develop a comprehensive framework for solar irrigation planning. The methodology is structured around two key components: Solar Suitability Mapping (SSM) and Solar Irrigation Pump Sizing Tool (SIP-ST). (Figure 2 - a, b). The module on SSM uses Geographic Information Systems (GIS) to identify areas with high potential for solar irrigation. The analysis integrates multiple datasets, including solar irradiance, groundwater depth, soil characteristics, land use, and infrastructure accessibility. Each parameter is standardized and assigned a weight based on its relative importance in determining suitability. A composite index is then generated to classify areas into different suitability categories. The module on SIP-ST complements the spatial analysis by providing farm-level optimization of irrigation systems.



Figure 2(a). Web-based Module on Solar Suitability Mapping

The tool calculates crop water requirements using climatic data and crop coefficients. It then determines the total dynamic head based on groundwater depth, pipe characteristics, and irrigation method. These inputs are used to estimate the required pump capacity and solar panel size. The integration of these two tools enables a comprehensive assessment of where and how solar irrigation systems should be deployed. This approach ensures that investments are targeted toward areas with high potential, while minimizing risks associated with groundwater depletion and system inefficiencies.



Figure 2(b). Web-based Module on Solar Irrigation Pump Sizing Tool

RESULTS AND DISCUSSION

Results reveal significant spatial variability in solar irrigation potential across Punjab. Figure 3 shows that Southern districts exhibit high suitability due to favorable solar irradiance, manageable groundwater depths, and suitable agricultural conditions.

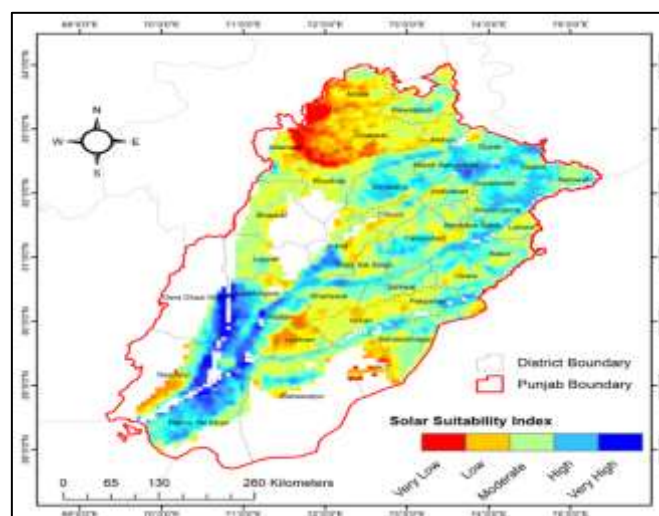


Figure 3. Solar Suitability Map of Punjab

In contrast, Northern districts show lower suitability due to deeper groundwater levels and less favorable infrastructure conditions. SIP-ST demonstrates the importance of system optimization in improving efficiency and sustainability. Properly sized pumps reduce energy consumption, lower installation costs, and minimize the risk of over-extraction. The analysis shows that smaller, appropriately sized systems are better suited to smallholder farmers, whereas larger systems may be required for intensive agricultural operations.

The integration of solar irrigation with HEIS further enhances water savings and productivity. By reducing water losses and improving application efficiency, these systems can significantly contribute to sustainable water management. The deployment of SSM and SIP-ST web-based modules represents a transformative step towards achieving sustainable, inclusive, and climate-resilient agricultural growth in Pakistan. Together, these tools provide an integrated framework to guide investments in SPIS to further ensure that solarization efforts are scientifically informed, economically viable, and environmentally responsible.

The SSM and SIP-ST web-based modules do not work in isolation rather, they enable cross-sectoral integration of Pakistan's agricultural, energy, and climate commitments. By ensuring efficient groundwater use, optimizing solar irrigation deployment, and reducing farmer energy costs, these tools directly contribute to multiple Sustainable Development Goals (SDGs), including SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action), while supporting Punjab's leadership in piloting evidence-based agricultural transformation.

The findings highlight the importance of combining technological innovation with policy and governance frameworks. Without proper regulation, the benefits of solar irrigation may be offset by increased pressure on groundwater resources. Therefore, a balanced approach that integrates renewable energy adoption with water management is essential.

CONCLUSION

Punjab, Pakistan, stands at a critical juncture in its agricultural transformation, where the transition to SPIS offers substantial benefits for improving livelihoods, enhancing food security, and advancing multiple Sustainable Development Goals (SDGs). Solar irrigation technologies directly contribute to poverty alleviation by increasing farmers' incomes and reducing operational costs, with evidence showing that solar pumps have initial costs 2-4 times lower than diesel alternatives, while providing cost-effective, environmentally friendly solutions with minimal maintenance requirements. These

systems enhance food security by supporting pressurized irrigation, enabling crop diversification, and increasing agricultural productivity across previously marginal lands. Furthermore, SPIS advances clean water and sanitation goals by improving irrigation efficiency and reducing water use at the field level, while simultaneously promoting affordable and clean energy by displacing fossil-fuel-based pumping systems. The climate action dimension is particularly significant, as solar irrigation reduces carbon footprints by avoiding CO₂ emissions from diesel and grid-based electricity thereby contributing to Pakistan's climate resilience objectives and supporting the transition toward low-carbon agricultural futures.

However, the expansion of SPIS in Punjab poses substantial risks of exacerbating groundwater depletion, over-extraction, and water quality degradation, which must be addressed through comprehensive governance frameworks. Pakistan ranks fourth globally in groundwater abstraction, with irrigation depleting fossil groundwater reserves by over 30 km³ per year in the Indus River Basin, resulting in a 69% depletion rate (55 km³ yr⁻¹ abstraction versus 37 km³ yr⁻¹ recharge) as of 2000. The country's agricultural sector currently uses approximately 60 billion m³ of groundwater annually for irrigation, leading to widespread overexploitation, aquifer stress, and declining water tables, posing fundamental threats to sustainable development and climate change adaptation. Unregulated SPIS expansion intensifies these challenges by enabling continuous, low-cost pumping, removing traditional economic constraints on groundwater extraction, particularly in regions where surface water supplies are insufficient. The environmental impacts extend beyond depletion to include water-quality degradation, increased energy use for deeper extraction, and cascading effects on domestic and industrial water availability. Without robust regulatory mechanisms, the zero marginal cost of solar energy paradoxically transforms a clean technology into a driver of unsustainable resource exploitation, threatening the long-term viability of Punjab's agricultural systems.

This study demonstrates that SPIS offers a viable solution to address Punjab's interconnected water-energy-climate challenges, provided its implementation is guided by data-driven, integrated planning frameworks that explicitly align energy transitions with groundwater sustainability imperatives. The combined deployment of Solar Suitability Mapping (SSM) and the Solar Irrigation Planning Spatial Tool (SIP-ST) provides a comprehensive, spatially explicit framework for planning and implementing solar irrigation systems that accounts for both technical feasibility and environmental constraints. SSM enables the identification of optimal locations for SPIS deployment by integrating solar irradiance data, land-use patterns, grid connectivity, and hydrogeological characteristics thereby ensuring that installations are concentrated in areas with adequate renewable groundwater resources or where conjunctive-use strategies can be implemented. SIP-ST complements this approach by incorporating real-time monitoring capabilities, groundwater-level tracking, and multi-criteria decision support that links irrigation scheduling to aquifer recharge dynamics and sustainable-yield thresholds. Together, these tools enhance system efficiency by optimizing pump sizing and panel configurations, reducing implementation costs through targeted site selection and avoiding malinvestment in hydrogeologically unsuitable areas, and supporting sustainable water use by embedding groundwater-sensitive planning criteria directly into the deployment process. The integration of artificial intelligence-driven monitoring, IoT-based environmental sensing, and cloud-satellite data further strengthens this framework by enabling adaptive management responses to changing groundwater conditions and climate variability. Successful scaling of sustainable SPIS in Punjab requires a multi-dimensional policy and financing architecture that addresses groundwater governance, promotes technology bundling, enables climate-smart financing mechanisms, and prioritizes social inclusivity. Groundwater governance reforms must establish clear extraction limits, implement volumetric monitoring systems, and create regulatory frameworks that link SPIS subsidies to compliance with sustainable pumping thresholds and participation in groundwater management institutions. The bundling of solar pumps with HEIS such as drip and sprinkler technologies is essential for translating energy savings into actual water conservation. Climate-smart financing approaches should leverage blended finance models that combine public subsidies, carbon credits, and private investment to reduce upfront costs for smallholder farmers, while incentivizing the adoption of water-saving technologies.

By embedding groundwater-sensitive planning through tools like SSM and SIP-ST, incentivizing solar-HEIS technology bundles that couple energy efficiency with water conservation, enabling climate-

smart financing that reduces barriers for smallholder adoption, and prioritizing inclusivity to ensure equitable access across socioeconomic strata, this integrated roadmap can set Punjab, Pakistan, on a transformative pathway toward a resilient, sustainable, and low-carbon agricultural future. The findings underscore the critical importance of policy integration across the water, energy, and food sectors, technological innovation that addresses both efficiency and sustainability dimensions, and meaningful stakeholder engagement that incorporates farmers' knowledge, institutional capacity, and community priorities to achieve climate-resilient agriculture. The water-energy-food nexus framework provides an essential analytical lens for understanding how interventions in one sector generate cascading effects across others, highlighting the need for coordinated governance structures that transcend traditional sectoral boundaries. Punjab can leverage solar irrigation not merely as a technological substitution, but as a catalyst for comprehensive agricultural transformation that improves productivity, reduces emissions, ensures long-term sustainability of groundwater resources, and advances multiple SDGs in Pakistan's most critical agricultural region.

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