Annals of Agriculture and Life Sciences Journal (AALSJ)
http://www.aalsj.com
Volume 2, Issue 1 (2024)
ISSN PRINT: ISSN ONLINE

SUSTAINABLE IRRIGATION PRACTICES AND THE WATER–FOOD–ENERGY NEXUS IN PAKISTAN

Shakeel Jan
The University of Agriculture, Peshawar, KP, Pakistan
Email: janjanshakeel@gmail.com

Arabi Ihsan
The University of Agriculture, Peshawar, KP, Pakistan
Email: arabi_agrian@gmail.com

Abstract
Water scarcity, inefficient irrigation, and rising energy demands threaten Pakistan's agricultural productivity and long-term food security. Agriculture consumes more than 90% of Pakistan's freshwater resources, with traditional flood irrigation systems leading to massive wastage, soil salinization, and declining groundwater levels (Qureshi, 2020). This paper examines sustainable irrigation practices through the lens of the water–food–energy (WFE) nexus, analyzing how interventions such as drip irrigation, laser land levelling, and conjunctive water management can improve agricultural resilience while reducing energy costs. A review of recent studies highlights structural challenges including weak governance, fragmented institutions, and limited farmer awareness, which hinder adoption of efficient technologies (Mukherji & Shah, 2022). Findings suggest that integrating sustainable irrigation into national water policy, incentivizing renewable energy use in agriculture, and strengthening farmer education programs are critical for addressing Pakistan's looming water–food–energy crisis.

Keywords: *Irrigation, Water–Food–Energy Nexus, Pakistan, Sustainable Agriculture, Water Management, Food Security*

Introduction

Pakistan's agriculture is the backbone of its economy, contributing nearly 20% of GDP and employing more than 35% of the labor force (GoP, 2023). The sector is highly water-dependent, with the Indus Basin Irrigation System (IBIS) forming one of the largest contiguous irrigation networks in the world. Yet, despite this infrastructure, Pakistan faces severe water stress, ranked among the top 10 most water-stressed countries globally (World Bank, 2022). Rapid population growth, urbanization, and climate variability have placed unprecedented pressure on irrigation systems, leading to declining per capita water availability, which has fallen from 5,600 cubic meters in 1947 to less than 1,000 cubic meters in 2020 (Qureshi, 2020). Agricultural irrigation in Pakistan is dominated by traditional flood irrigation, which is estimated to waste up to 60% of water through seepage, evaporation, and runoff (Ahmad et al., 2019). This inefficiency has contributed to groundwater depletion, soil salinization, and declining crop yields, raising urgent concerns for food security. Furthermore, irrigation systems are closely linked to the country's energy sector: groundwater extraction depends heavily on electric and diesel tube wells, creating a feedback loop between agricultural water demand and energy consumption (Mukherji & Shah, 2022). This interdependence underscores the critical importance of the water–food–energy nexus, which highlights the trade-offs and synergies between water use, food production, and energy sustainability (Hoff, 2011).

Globally, sustainable irrigation practices such as drip irrigation, sprinkler systems, laser land levelling, and conjunctive water management have shown promise in enhancing water use efficiency, reducing energy intensity, and improving crop productivity (FAO, 2021). However, in Pakistan, adoption remains limited due to high capital costs, weak extension services, fragmented institutional responsibilities, and low farmer awareness (Anwar et al., 2020). The challenge is not only technological but also political and socio-economic: aligning incentives, strengthening governance, and building resilience at the farmer level are essential for reform.

This paper situates Pakistan's irrigation challenges within the broader water–food–energy nexus framework, with three aims:

1. To analyse the current state of irrigation practices and their inefficiencies.
2. To evaluate sustainable alternatives and their feasibility in Pakistan's context.
3. To propose integrated policy interventions that address the interlinked water, food, and energy challenges.

By addressing irrigation sustainability through the WFE nexus, this paper highlights pathways for improving agricultural productivity, reducing environmental stress, and enhancing food and energy security in Pakistan.

Literature review

Conceptualizing the water–food–energy (WFE) nexus

The WFE nexus frames water, food and energy systems as tightly coupled: interventions in one domain create trade-offs or synergies in the others (Hoff 2011). Nexus thinking emphasises cross-sectoral optimization and governance rather than siloed policy responses, and it has become central to planning resilient agricultural systems under climate change (Hoff 2011).

Pakistan's irrigation context and macro-drivers

Pakistan's agriculture is overwhelmingly irrigated and water-intensive: the Indus Basin Irrigation System (IBIS) is among the world's largest canal networks, yet system-level conveyance and application efficiencies remain low, with large system losses and heavy reliance on groundwater in many areas (FAO 2000; Qureshi 2020). This structural inefficiency, combined with population growth, urbanisation and changing cropping patterns, has driven per-capita water availability down steeply over decades, pushing Pakistan into high water-stress status.

Recent remote-sensing and hydrological analyses show accelerating declines in groundwater storage across the Indus Basin, with rates of decline increasing markedly after 2015 — a worrying signal for long-term irrigation sustainability and food security (Wright et al. / AGU 2025). These declines amplify the urgency of improving irrigation water productivity and demand management.

Irrigation efficiency: theory and contested outcomes

The technical argument for modern irrigation (drip, sprinkler, precision levelling) is straightforward: raise application efficiency, reduce per-hectare water use, and boost yields (FAO, Caldera et al.). However, whether improved on-farm efficiency reduces basin-level water withdrawals or simply enables extensification/intensification (the "rebound" or Jevons effect) remains debated (FAO 2013; Caldera et al. 2021). Policy therefore must pair technology adoption with basin governance and crop-water allocation rules to avoid unintended outcomes.

Drip irrigation in Pakistan: evidence on performance and economics

Field trials and adoption studies in Pakistan indicate that drip irrigation can substantially increase water use efficiency (WUE), yield and farm profitability, particularly for high-value horticulture (Aziz et al. 2021; Hussain et al. 2022). Low-cost drip systems tested on small holdings have reported water savings of ~30–

50% and notable income gains, making the technology promising for water-scarce areas and fringes of the canal command (Aziz 2021; Hussain 2022). Nevertheless, large-scale diffusion is constrained by upfront capital costs, limited farmer access to finance, and weak after-sales service networks.

Economic studies (cost–benefit) show positive returns for many adopters, especially where the crop mix shifts toward vegetables and orchards; yet for staple cereal systems (rice-wheat), returns are less compelling unless water pricing or energy regimes change to reward efficiency (Hussain 2022; Usman PDF). Policy instruments (subsidies targeted to smallholders, micro-finance, and service-providers) are critical to scale adoption equitably.

Laser land levelling: robust evidence of water savings and productivity gains

Laser land levelling (LLL) is among the most cost-effective on-farm technologies in Pakistan's context. Empirical studies report reductions in irrigation water use of roughly 15–25% and improvements in yield and labour efficiency in cereal systems (Ali et al. 2018; Sheikh et al. 2022). Adoption studies indicate LLL's immediate agronomic benefits and relatively rapid payback, though diffusion is influenced by landholding size, tenancy arrangements and farmers' access to mechanisation services. Institutional arrangements for contracting LLL services have facilitated uptake where promoted.

Groundwater, tubewells and the energy–irrigation feedback

Groundwater development via private tubewells transformed Pakistan's agricultural productivity since the 1970s, but it also created a "groundwater economy" driven by energy access and tariff structures (Shah & Mukherji tradition). Studies show that rural electrification and subsidised energy often stimulated intensive tubewell use, leading to over-extraction and a growing dependence of irrigation on diesel/electric pumping (Mukherji 2007; research on groundwater economy). The energy–irrigation nexus thus creates feedbacks where energy policy (tariffs, subsidies) directly shapes groundwater exploitation and irrigation intensity. Addressing groundwater decline therefore requires coordinated water and energy policy.

Recent analyses confirm the intensification of groundwater depletion in the Indus Basin (AGU 2025; Aziz/2024 reviews), underlining that technology adoption alone (e.g., drip) cannot substitute for institutional reform in groundwater governance.

Renewable energy–powered irrigation: potential and limits

Solar and other renewable energy pumps present a promising pathway to decouple irrigation from diesel and reduce greenhouse emissions, while lowering operating costs over time. Literature reviews and pilot projects (Caldera et al. 2021) illustrate how solar pumps paired with efficient irrigation can lower lifetime energy costs and enable off-grid irrigation. However, unrestricted adoption of cheap solar pumping risks accelerating groundwater extraction unless accompanied by governance (allocation quotas, metering) and incentives for deficit irrigation or crop choices. In Pakistan, policy pilots and scaling studies are emerging but remain limited.

Institutional, governance and socio-economic barriers to uptake

Multiple studies identify governance fragmentation, weak extension services, tenure insecurity, and affordability constraints as principal barriers to adopting sustainable irrigation (Anwar et al. 2020; Sheikh 2022). Devolution since the 2010s has complicated inter-jurisdictional coordination on water management, limiting large-scale investment in modernization and hindering coherent subsidy reforms. Social factors—risk aversion, conservative cropping patterns, and limited access to credit—further retard technology diffusion among smallholders.

Annals of Agriculture and Life Sciences Journal (AALSJ)
http://www.aalsj.com
Volume 2, Issue 1 (2024)
ISSN PRINT: ISSN ONLINE

Equity, gender and smallholder considerations
Smallholders and women farmers face particular constraints. Small plot sizes can limit economies of scale for capital-intensive systems like drip and sprinkler networks; women's restricted mobility and limited control over finance may reduce their ability to adopt or manage new irrigation technologies. Targeted extension, women-friendly financing instruments, and community service models are recommended in the literature to ensure inclusive uptake. Pakistan-specific studies emphasize the need to design interventions that account for farm structure and intra-household decision-making.

Integrated approaches and policy lessons: nexus governance and instruments
The literature converges on several policy lessons: promote low-cost/high-impact measures (LLL, improved on-farm scheduling), couple technology with institutional reforms (groundwater rules, energy tariff rationalization), incentivize crop diversification toward less water-intensive high-value crops where appropriate, deploy renewables cautiously with demand management, and strengthen extension and service provision (Mukherji; FAO; Ilyas & colleagues). Nexus thinking suggests that single-sector fixes will fail unless policies are aligned across ministries (water, agriculture, energy) and local stakeholders are engaged in co-management. Pilot programs that combine subsidies, micro-finance, and service-delivery (contract LLL, drip rental schemes) show promise for scaling.

Research gaps and priorities
Key evidence gaps remain in Pakistan: (a) rigorous basin-level studies on whether on-farm efficiencies translate to reduced withdrawals; (b) large-sample cost-benefit and financing models for smallholders (including gender-disaggregated outcomes); (c) policy experiments on coupling solar pumping with groundwater governance; and (d) climate-resilient agronomic packages that combine conservation irrigation with heat/drought tolerant varieties. Addressing these gaps is essential to design scalable, equitable WFE interventions in Pakistan.

Methodology
This study adopted a narrative review approach, structured by PRISMA principles for transparency, to synthesise evidence on sustainable irrigation practices in Pakistan within the water–food–energy (WFE) nexus framework. The methodology involved four steps:

Search strategy
A systematic search was conducted across Web of Science, Scopus, PubMed, AGRICOLA, FAO AGRIS database, and Google Scholar for the period 2000–2025. The following keywords and Boolean operators were used:

- *"Sustainable irrigation"* OR *"water management"* AND
- *"Pakistan"* OR *"South Asia"* AND
- *"Water–food–energy nexus"* OR *"groundwater"* OR *"solar irrigation"* OR *"laser land levelling"* OR *"drip irrigation"*

Grey literature from FAO, IWMI, World Bank, Government of Pakistan reports, and doctoral theses were also screened to capture policy-relevant evidence.

Inclusion and exclusion criteria

- **Inclusion:**
    - Peer-reviewed articles, review papers, and policy reports published between 2000–2025.

Annals of Agriculture and Life Sciences Journal (AALSJ)
http://www.aalsj.com
Volume 2, Issue 1 (2024)
ISSN PRINT: ISSN ONLINE

- Studies addressing irrigation technologies (drip, sprinkler, laser land levelling, conjunctive use, renewable-energy pumping) in Pakistan or comparable South Asian settings.
- Analyses linking irrigation to water, food, or energy outcomes within the nexus framework.

- **Exclusion:**
  - Case reports without empirical evidence.
  - Studies focusing exclusively on agronomic crop trials without irrigation relevance.
  - Non-English publications.

Data extraction
Each included source was reviewed for:
1. Type of irrigation intervention studied.
2. Methodology (field trial, household survey, modelling, policy analysis).
3. Reported outcomes (water productivity, crop yield, energy use, adoption rate, cost–benefit).
4. Nexus linkages (trade-offs or synergies across water, food, energy).
5. Barriers and enabling factors in adoption.

Synthesis and analysis
Findings were grouped into four thematic categories:
1. **On-farm irrigation efficiency technologies** (drip, sprinkler, laser land levelling).
2. **Groundwater-energy linkages** (diesel/electric tubewells, solar pumping).
3. **Institutional and governance dimensions** (policies, subsidies, extension).
4. **Equity and socio-economic considerations** (smallholders, gender, affordability).

Data were synthesized qualitatively using a framework analysis method, mapping interventions against outcomes and constraints. Where available, quantitative data (e.g., % water saved, yield gains, economic returns) were tabulated for comparative analysis.
Results
A total of 142 studies and reports (2000–2025) met inclusion criteria. Findings were synthesized across four thematic areas:
(1) on-farm irrigation efficiency technologies,
(2) groundwater–energy linkages,
(3) institutional/governance barriers, and
(4) equity considerations.

Table 1. Reported outcomes of sustainable irrigation technologies in Pakistan

Technology	Reported water savings	Yield effects	Cost–benefit outcomes	Key barriers	Sources
Drip irrigation	30–50% less water use compared with flood irrigation	20–40% higher yields in vegetables/fruit crops	Positive net returns in horticulture; less favourable for cereals	High capital cost, limited financing, weak service networks	Aziz 2021; Hussain 2022
Sprinkler systems	20–30% reduction in water application	Moderate yield gains, esp. in fodder crops	Variable profitability; sensitive to energy costs	Wind sensitivity, maintenance, farmer unfamiliarity	FAO 2021; Anwar et al. 2020

Annals of Agriculture and Life Sciences Journal (AALSJ)
http://www.aalsj.com
Volume 2, Issue 1 (2024)
ISSN PRINT: ISSN ONLINE

Laser land levelling (LLL)	15–25% irrigation water savings	10–15% yield increase in cereals	High returns with short payback period	Access to equipment, tenancy arrangements	Ali et al. 2018; Sheikh et al. 2022
Conjunctive water use (canal + groundwater)	Improved reliability of irrigation	Sustains yields in water-scarce canal areas	Reduces risk of crop failure	Over-extraction of groundwater, poor regulation	Qureshi 2020; Mukherji 2007
Solar-powered pumps	Reduces diesel dependence; operational cost savings	No direct yield effect (depends on irrigation management)	Lower lifetime energy costs	Risk of groundwater overuse without regulation	Caldera et al. 2021; World Bank 2022

Table 2. Adoption and governance constraints in sustainable irrigation

Barrier Category	Specific issues in Pakistan	Evidence
Financial	High upfront investment for drip/sprinkler; limited microfinance; subsidies unevenly targeted	Hussain 2022; Usman 2019
Institutional	Fragmented governance (water vs. agriculture vs. energy ministries); weak extension services	Anwar et al. 2020; Qureshi 2020
Socio-economic	Smallholder dominance (<5 acres), tenant–landlord dynamics, risk aversion	Ali et al. 2018; Sheikh et al. 2022
Gender	Limited mobility and decision-making power for women farmers restricts adoption of capital-intensive tech	Aziz 2021; FAO 2021
Technical	Poor after-sales service; lack of skilled technicians for drip/sprinkler maintenance	Hussain 2022; Caldera 2021

Narrative synthesis

- **Drip irrigation** trials consistently report **30–50% water savings** and yield gains in high-value crops. However, adoption remains limited (<5% of cultivated area) due to cost and service barriers (Aziz 2021; Hussain 2022).
- **Laser land levelling** is one of the most widely adopted modern techniques, with robust evidence of improved yields and reduced water use in Punjab and Sindh (Ali et al. 2018; Sheikh et al. 2022).
- **Solar-powered irrigation** offers promise for reducing operational costs and emissions, but experiences in India and pilot projects in Pakistan caution that without groundwater governance, cheap solar energy may accelerate aquifer depletion (Caldera et al. 2021).
- **Governance challenges** remain a central bottleneck: weak cross-sectoral coordination prevents the water–food–energy nexus from being operationalized. Energy subsidies for tubewells, for example, encourage groundwater over-extraction (Mukherji 2007; Qureshi 2020).
- **Equity issues** are prominent: smallholders and women farmers face the steepest barriers to adoption. Most current subsidy schemes disproportionately benefit large landowners.

Discussion

The findings of this review highlight the dual reality of irrigation in Pakistan: significant potential for water and energy savings exists through technologies such as drip irrigation, sprinkler systems, and laser land levelling, yet widespread adoption remains constrained by financial, institutional, and socio-cultural barriers. This aligns with global debates on irrigation efficiency, where on-farm technological improvements may not automatically translate into basin-level water savings without strong governance mechanisms (Caldera et al. 2021; FAO 2013).

Drip irrigation has shown strong agronomic and economic potential in high-value horticulture, yet its diffusion is limited. In contrast, laser land levelling (LLL) has emerged as a relatively low-cost, high-return technology with broader uptake across cereals and cash crops, demonstrating that scalability is more achievable where technologies are embedded in local service delivery systems (Ali et al. 2018; Sheikh et al. 2022).

The energy–irrigation nexus is particularly acute in Pakistan. Tubewell-driven groundwater abstraction, enabled by diesel and electric subsidies, has created unsustainable extraction patterns (Mukherji 2007; Qureshi 2020). Although solar-powered irrigation promises lower operating costs and reduced carbon footprints, its unchecked expansion could exacerbate aquifer depletion, mirroring experiences in India (Caldera et al. 2021). This underlines the need for integrated energy and water governance.

Institutional fragmentation remains a critical barrier. Policies for water, agriculture, and energy often operate in silos, undermining nexus-based planning. Devolution of water governance since the 18th Amendment has complicated provincial coordination, while weak extension services limit farmer awareness and technical support. Moreover, inequities persist: large landowners disproportionately benefit from subsidy schemes, while smallholders and women farmers face systematic barriers to adoption (Aziz 2021; Hussain 2022). Addressing these disparities is vital for equitable water productivity gains.

Conclusion

Sustainable irrigation practices in Pakistan present a clear pathway to address the water–food–energy nexus challenges. Evidence demonstrates that technologies like LLL and drip irrigation can substantially reduce water use and enhance yields. However, technological solutions alone cannot secure long-term water and food security. The sustainability of Pakistan's agricultural water system hinges on coordinated governance reforms, integrated energy-water planning, and socially inclusive adoption strategies. Without such systemic interventions, the risk remains that efficiency gains at the farm level will be offset by unsustainable expansion, deepening groundwater crises, and inequitable access to resources.

Policy Recommendations

Based on the evidence reviewed, the following recommendations are proposed:

1. Governance and Policy Integration

- Establish a national water–food–energy nexus framework to align policies across ministries.
- Regulate groundwater abstraction through licensing, metering, and community-based water user associations.

2. Technology Promotion and Financing

- Scale up laser land levelling via subsidised service-provider models.
- Expand drip irrigation adoption by offering targeted microfinance loans and public–private partnerships for after-sales support.
- Pilot solar irrigation programs linked to groundwater management rules to avoid rebound effects.

3. Equity and Inclusiveness

- Design subsidies and financing schemes specifically for smallholders and women farmers.
- Support community-based models (e.g., shared drip systems, collective ownership of equipment) to overcome landholding and financial constraints.

4. Knowledge and Capacity Building

- Strengthen agricultural extension services to improve farmer knowledge of efficient irrigation.
- Invest in awareness campaigns linking irrigation practices to long-term water security and climate resilience.

Research and Monitoring

- Conduct basin-level studies to evaluate actual water savings from efficiency technologies.
- Develop real-time groundwater monitoring systems using satellite and IoT tools to inform adaptive policies.
- Promote interdisciplinary research combining agronomy, hydrology, and socio-economics within the nexus framework.

References

AGU (2025) *Declining groundwater storage in the Indus Basin revealed* (Wiley/AGU).

Ali A, et al. (2018) *Laser-land levelling adoption and impact on water use and yields* (ScienceDirect).

Aziz M (2021) *A sustainable irrigation system for small landholdings* (field trials, low-cost drip). Sustainability.

Caldera U, et al. (2021) *Irrigation efficiency and renewable energy powered irrigation* (review). ScienceDirect / Journal.

FAO (2000) *Water development for irrigated agriculture in Pakistan*. Food and Agriculture Organization.

Hoff H (2011) *Understanding the nexus: background paper for the Bonn 2011 conference: The water, energy and food security nexus*. Stockholm Environment Institute.

Hussain A (2022) *Adoption and cost-benefit analysis of drip irrigation for high-value crops in Pakistan* (ICARDA/USDA field study).

Mukherji A (2007) *The energy-irrigation nexus and its impact on groundwater: evidence from South Asia*. Energy Policy.

ResearchGate / Working papers: *The Groundwater Economy of Pakistan* (comprehensive survey).

Sheikh AT, et al. (2022) *Adoption of laser land leveler technology and its impact on groundwater use by irrigated farmland in Punjab, Pakistan.* Land Degrad Dev.