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Development of A Data-Envelopment-Analysis-Based Hydrological Vulnerability Index for Sustainable Watershed Management in Indian River Basins

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Abstract
River Lift Irrigation Systems (RLIS) play an important role in improving irrigation access in regions with undulating terrain and limited canal irrigation facilities. The present study evaluates the technical and economic performance of RLIS in the Ajay River Basin, Jharkhand. The research examines pump efficiency, water conveyance performance, energy consumption, operational costs, and agricultural benefits associated with irrigation systems. Primary data were collected through field surveys, technical observations, and farmer interviews, while economic feasibility was assessed using indicators such as Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Internal Rate of Return (IRR). The findings indicate that RLIS significantly enhance cropping intensity and agricultural productivity; however, system performance is constrained by high energy costs, poor maintenance, and institutional challenges. The study emphasizes the need for energy-efficient technologies, participatory irrigation management, and sustainable operational strategies to improve the long-term viability of RLIS in the Ajay River Basin, Jharkhand.

Keywords
River Lift Irrigation Systems, Techno-Economic Evaluation, Irrigation Efficiency, Sustainable Irrigation Management, Ajay River Basin, Jharkhand

1. Introduction

Agriculture plays a vital role in the Indian economy and remains the primary source of livelihood for a large proportion of the rural population. However, agricultural productivity in many parts of India is constrained by inadequate irrigation infrastructure and heavy dependence on monsoon rainfall. In Eastern India, particularly in Jharkhand, the situation is more critical due to uneven topography, seasonal variability in rainfall, and limited irrigation facilities. Although the region possesses significant surface water resources through rivers and streams, much of this potential remains underutilized because conventional gravity-based irrigation systems are not feasible in upland and plateau regions (Dhawan, 1988). River Lift Irrigation Systems (RLIS) have emerged as an important alternative irrigation strategy in such areas. RLIS involve lifting water from rivers through mechanical pumping systems and distributing it to agricultural fields situated at higher elevations. These systems are particularly suitable for regions like the Ajay River Basin, where agriculture is predominantly rain-fed and irrigation coverage remains limited despite the availability of river water resources. By improving access to irrigation water, RLIS have the potential to enhance cropping intensity, increase agricultural productivity, and improve rural livelihoods (Lamichhane et al., 2024)

Despite their advantages, the performance and sustainability of RLIS are affected by several technical, economic, and institutional challenges. Problems such as low pump efficiency, high energy consumption, poor maintenance, irregular electricity supply, and weak community participation often reduce operational effectiveness and increase irrigation costs. In many cases, these challenges result in underutilization or failure of irrigation systems, limiting their long-term sustainability (Chand et al., 2024).

The present study therefore aims to evaluate the techno-economic performance and sustainable management of RLIS in the Ajay River Basin, Jharkhand. The study focuses on technical efficiency, economic viability, energy consumption, institutional participation, and sustainability concerns associated with irrigation systems. By integrating technical, economic, and social dimensions, the research seeks to provide a comprehensive framework for improving the long-term sustainability and effectiveness of RLIS in Eastern India (Yadav et al., 2022).

2. Literature Review

Irrigation has historically played a crucial role in agricultural development by ensuring reliable water supply for crop cultivation and reducing dependence on rainfall. In developing countries such as India, irrigation systems have contributed significantly to increasing agricultural productivity, enhancing food security, and supporting rural livelihoods. However, the rapid expansion of irrigation infrastructure has also generated several technical, economic, environmental, and institutional challenges, particularly in regions characterized by limited water management capacity and uneven resource distribution. Consequently, researchers and policymakers have increasingly emphasized the need for sustainable irrigation systems that integrate technical efficiency with economic viability and environmental sustainability (Dhawan, 2017).

The development of irrigation systems in India has evolved through multiple stages, ranging from traditional water harvesting structures to modern large-scale canal and lift irrigation projects. During the Green Revolution period, major emphasis was placed on expanding irrigation infrastructure to support intensive agriculture and increase food grain production. While these interventions improved agricultural output in several regions, they also created regional disparities in irrigation development. North-western states experienced substantial growth in irrigation coverage through canal systems and groundwater extraction, whereas Eastern India continued to depend heavily on rainfall despite having considerable surface water resources (Gulati & Banerjee, 2015).

Eastern India presents a unique irrigation paradox where abundant water availability coexists with low irrigation development and agricultural underperformance. Studies have shown that despite receiving high annual rainfall, states such as Jharkhand, Bihar, Odisha, and West Bengal continue to experience low cropping intensity and limited irrigation coverage due to inadequate infrastructure and poor water management practices. Amarasinghe et al. (2009) observed that ineffective utilization of surface water resources remains one of the major constraints to agricultural development in Eastern India. The region's undulating terrain, fragmented landholdings, and limited storage structures further complicate irrigation development, thereby necessitating the adoption of alternative irrigation approaches suitable for local geographical conditions (Raju & Daisy, n.d.).

River Lift Irrigation Systems (RLIS) have emerged as an important irrigation strategy for regions where gravity-based irrigation is technically infeasible. RLIS involve lifting water from rivers or streams using mechanical pumping systems and distributing it to agricultural fields situated at higher elevations. Such systems are particularly relevant in plateau and upland regions like Jharkhand, where conventional canal irrigation systems are difficult to implement. According to Dhawan (1988), RLIS can significantly improve irrigation accessibility by utilizing underexploited surface water resources and expanding irrigation coverage in topographically constrained areas (Dhawan, 1988).

Several studies have examined the technical performance of lift irrigation systems in India. Kumar and Singh (2018) reported that many lift irrigation projects suffer from low operational efficiency due to outdated pumping technologies, poor maintenance practices, and high conveyance losses. Technical inefficiencies often arise from improper pump selection, leakages in distribution networks, sedimentation in intake structures, and inadequate system monitoring. These inefficiencies reduce water delivery performance and increase operational costs, ultimately affecting the overall sustainability of irrigation systems.

Energy consumption has been identified as one of the most significant challenges affecting the performance and sustainability of RLIS. Since water lifting requires substantial energy input, operational costs are heavily influenced by energy expenditure. In many rural regions, unreliable electricity supply and rising diesel prices create major constraints for irrigation operations (Lamichhane et al., 2024). Shah et al. (2012) highlighted that dependence on diesel-powered pumping systems not only increases operational costs but also contributes to environmental degradation through greenhouse gas emissions. As a result, researchers have increasingly advocated the adoption of renewable energy-based irrigation systems, particularly solar-powered pumps, to improve energy efficiency and reduce operational costs (Yadav et al., 2022).

Economic evaluation constitutes another important area of irrigation research. Techno-economic assessment enables the analysis of irrigation system viability by comparing costs incurred with benefits generated through agricultural production. Gittinger (1972) emphasized that irrigation projects should be evaluated not only on the basis of engineering feasibility but also in terms of long-term financial sustainability and economic returns. Commonly used economic indicators in irrigation studies include Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Internal Rate of Return (IRR) (Gittinger, 1972). Studies conducted in different parts of India have shown that the economic performance of irrigation systems depends largely on factors such as command area size, cropping intensity, water distribution efficiency, and energy expenditure (Mishra et al., 2011)

Research on RLIS in Eastern India has revealed mixed outcomes regarding economic viability. While some projects have successfully improved crop productivity and farmer income, others have faced challenges related to high operational costs and poor maintenance. Sahu et al. (2020) observed that irrigation systems with efficient pumping mechanisms and proper management structures generated better economic returns compared to poorly maintained systems. Their study also highlighted the importance of regular maintenance and energy-efficient technologies in improving financial sustainability (Ray & Majumder, 2024).

Institutional and governance factors significantly influence the success of irrigation systems. Participatory Irrigation Management (PIM) has been widely promoted as a strategy for improving irrigation governance by involving farmers in decision-making and resource management. Water User Associations (WUAs) are considered important institutional mechanisms for ensuring equitable water distribution, maintenance of infrastructure, and collection of irrigation charges (Kulkarni et al., 2011). Gandhi et al. (2009) noted that community participation enhances accountability and improves operational efficiency of irrigation systems. However, the effectiveness of WUAs varies considerably depending on social cohesion, leadership quality, institutional support, and local governance structures (Gandhi et al., 2020).

In tribal and rural regions such as the Ajay River Basin, socio-economic conditions strongly influence irrigation management practices. Small and marginal farmers often face difficulties in contributing towards maintenance costs and participating effectively in collective irrigation management. Inadequate awareness, weak institutional coordination, and conflicts over water distribution further reduce system efficiency (Kalli et al., 2024). Several studies have indicated that the sustainability of community-managed irrigation systems depends on the level of social cooperation and trust among users (Fiaz et al., 2026).

Environmental sustainability has become increasingly important in irrigation research due to growing concerns regarding water scarcity, ecological degradation, and climate change. Excessive withdrawal of surface and groundwater resources can disrupt hydrological balance and reduce long-term water availability (Moon et al., 2026). The Intergovernmental Panel on Climate Change (IPCC, 2014) emphasized that climate variability is likely to intensify water-related challenges in agriculture, particularly in regions dependent on seasonal rainfall. Irrigation systems therefore need to incorporate climate-resilient and resource-efficient technologies to ensure long-term sustainability (Kikstra et al., 2022).

The concept of sustainable irrigation management extends beyond technical and economic performance to include environmental conservation and social equity (da-Silva-Branco et al., 2026). The Food and Agriculture Organization (FAO, 2017) emphasized that sustainable irrigation systems should promote efficient water use, minimize environmental impacts, ensure economic viability, and support equitable resource distribution. Integrating renewable energy technologies, improving irrigation efficiency, strengthening community participation, and adopting adaptive management practices are considered essential components of sustainable irrigation development (Taguta et al., 2022).

Despite extensive research on irrigation systems, there remains a significant gap in integrated studies focusing on the techno-economic and sustainability dimensions of RLIS in Eastern India. Most previous studies have concentrated either on technical performance or economic feasibility without adequately addressing institutional and environmental concerns. Furthermore, limited research has been conducted specifically in the context of the Ajay River Basin, Jharkhand, where irrigation challenges are shaped by unique geographical, socio-economic, and hydrological conditions. The present study seeks to address this gap by adopting a comprehensive framework that combines technical evaluation, economic analysis, and sustainability assessment to examine the performance and management of RLIS in the study area (Vasudevan & Natarajan, 2021).

3. Materials and Methodology

The present study adopted a mixed-method research approach to evaluate the technical performance, economic viability, and sustainability of River Lift Irrigation Systems (RLIS) in the Ajay River Basin, Jharkhand. Both quantitative and qualitative methods were employed to obtain a comprehensive understanding of irrigation system performance and management challenges (Malatsi et al., 2025). The study was conducted in selected RLIS command areas within the Ajay River Basin, which is characterized by undulating topography, seasonal variability in water availability, and predominance of rain-fed agriculture. The basin was selected due to the presence of multiple RLIS projects and the growing importance of irrigation for agricultural development in the region (Jha et al., 2011).

Both primary and secondary data sources were utilized for the study. Primary data were collected through structured household surveys, field observations, technical measurements, key informant interviews, and focus group discussions. Household surveys were conducted among beneficiary farmers to collect information related to landholding size, cropping pattern, irrigation frequency, crop productivity, operational costs, energy consumption, maintenance practices, and farm income (Yeleliere et al., 2023). Technical observations were carried out to assess the condition and operational efficiency of pumps, pipelines, intake structures, and distribution systems. Key informant interviews with irrigation officials, pump operators, and representatives of Water User Associations (WUAs) provided information related to institutional management, governance structures, maintenance practices, and irrigation scheduling. Focus group discussions were also organized to understand collective management practices, sustainability concerns, and operational challenges associated with RLIS (Yeleliere et al., 2023).

Secondary data were collected from government reports, irrigation department records, census reports, published literature, and meteorological databases. These sources provided information related to rainfall patterns, hydrological characteristics, irrigation infrastructure, socio-economic conditions, and agricultural practices within the Ajay River Basin (Pani et al., 2024). A multistage sampling technique was adopted for selecting study sites and respondents. Initially, selected RLIS projects were identified based on operational status, command area coverage, and accessibility (Sedgwick, 2015). Beneficiary villages associated with the selected irrigation projects were then identified, followed by random selection of farming households. A total of 150 respondents were surveyed for the study (Hando, 2021).

Technical performance assessment focused on evaluating pump efficiency, conveyance efficiency, water distribution performance, and energy consumption patterns. Pump efficiency was calculated by comparing output water power with input power using the following equation (Martin-Candilejo et al., 2020):

$$\text{Pump Efficiency} = \frac{\text{Water Output Power}}{\text{Input Power}} \times 100$$

Conveyance efficiency was estimated to determine water losses during transportation through pipelines and distribution systems using the following formula (Ali, 2010):

$$\text{Conveyance Efficiency} = \frac{\text{Water Delivered to Field}}{\text{Water Released from Source}} \times 100$$

Economic evaluation of RLIS was carried out through cost-benefit analysis considering capital investment, installation expenditure, maintenance costs, labor costs, and energy expenditure. Benefits were estimated based on increase in crop productivity, cropping intensity, irrigated area, and agricultural income. Financial viability of irrigation systems was assessed using Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Internal Rate of Return (IRR). Net Present Value was calculated using the following equation (Michalis et al., 2023):

$$\mathrm{NPV} = \sum \frac{\mathrm{Bt} - \mathrm{Ct}}{(1 + \mathrm{r})\mathrm{t}}$$

where Bt represents benefits in year t, Ct represents costs in year t, and r denotes the discount rate.
The Benefit-Cost Ratio was estimated using the following formula (Michalis et al., 2023):

$$\mathrm{BCR} = \frac{\text{Present Value of Benefits}}{\text{Present Value of Costs}}$$

Sustainability assessment included technical, economic, social, and environmental indicators. Technical indicators focused on system efficiency and maintenance condition, while economic indicators examined irrigation cost, profitability, and financial sustainability. Social indicators included institutional participation, equity in water distribution, and farmer satisfaction. Environmental indicators assessed water use efficiency, energy source, and environmental sustainability of irrigation practices (Gebeyehu, 2025).

The collected data were analyzed using Statistical Package for Social Sciences (SPSS), Microsoft Excel, and GIS-based techniques. Descriptive statistics, percentage analysis, frequency distribution, correlation analysis, regression analysis, and paired sample t-tests were employed to interpret the data and examine relationships among variables. Tables, graphs, and charts were prepared to present the results systematically. Although the study faced limitations related to seasonal variability, limited availability of long-term records, and dependence on farmer-reported data, efforts were made to ensure reliability and validity through field verification and triangulation of multiple data sources (Mweshi & Muhyila, 2024)

4. Results And Discussion

The present study evaluated the technical performance, economic viability, and sustainability dimensions of River Lift Irrigation Systems (RLIS) in the Ajay River Basin, Jharkhand using field survey data analyzed through SPSS statistical tools. The analysis was conducted using descriptive statistics, frequency distribution, correlation analysis, regression analysis, and paired sample t-tests to understand the operational efficiency and management challenges associated with RLIS (Singh et al., 2020).

4.2 Socio-Economic Profile of Respondents

Understanding the socio-economic characteristics of farmers is essential for assessing the effectiveness and sustainability of irrigation systems. SPSS frequency and percentage analysis were used to examine demographic and socio-economic characteristics of the respondents (Ravindranath, 2022).

4.2.1 Age Distribution of Respondents

The age-wise distribution of respondents indicated that the majority of farmers belonged to the economically active age group. SPSS frequency analysis revealed that approximately 46.7% of respondents were between 36–50 years of age, followed by 31.3% in the 51–65 years category. Only 12% of respondents were below 35 years of age (Issa et al., n.d.).

The findings suggest that middle-aged farmers constituted the dominant user group of RLIS in the study area. Farmers in this category were more actively involved in irrigation management and agricultural decision-making processes (Issa et al., n.d.).

Table 4.1 Age Distribution of Respondents

Age Group	Frequency	Percentage
Below 35 Years	18	12.0
36–50 Years	70	46.7
51–65 Years	47	31.3
Above 65 Years	15	10.0
Total	**150**	**100**

4.2.2 Landholding Size

SPSS descriptive statistics indicated that small and marginal farmers dominated the study area. Nearly 62% of respondents possessed landholdings below 2 hectares, while only 11% owned more than 5 hectares of agricultural land (Basantaray, 2025).

The predominance of small landholdings significantly influenced irrigation management practices and financial capacity for maintenance contributions (Basantaray, 2025).

Table 4.2 Landholding Size of Respondents

Landholding Category	Frequency	Percentage
Marginal (<1 ha)	52	34.7
Small (1–2 ha)	41	27.3
Medium (2–5 ha)	40	26.7
Large (>5 ha)	17	11.3
Total	**150**	**100**

4.3 Technical Performance Analysis of RLIS

4.3.1 Pump Efficiency Analysis

The efficiency of pumping systems was evaluated through field measurements and analyzed using SPSS descriptive statistics. The results revealed considerable variation in operational efficiency among RLIS projects (Martin-Candilejo et al., 2020).

The mean pump efficiency was recorded at 68.4%, with a standard deviation of 8.7, indicating moderate variability among irrigation systems. Systems equipped with recently installed pumps demonstrated comparatively higher efficiency levels than older systems (Martin-Candilejo et al., 2020).

Table 4.3 Descriptive Statistics of Pump Efficiency

Variable	Mean	Std. Deviation	Minimum	Maximum
Pump Efficiency (%)	68.4	8.7	52.0	82.0

The findings indicate that technical inefficiencies such as mechanical deterioration, sedimentation, and inadequate maintenance reduced the operational performance of irrigation systems (Martin-Candilejo et al., 2020).

4.3.2 Conveyance Efficiency

SPSS analysis showed that average conveyance efficiency ranged between 65% and 82%, with an overall mean value of 73.5% (Ali, 2010).
Leakages in pipelines, damaged distribution channels, and irregular maintenance practices contributed significantly to water losses during conveyance (Ali, 2010).

Table 4.4 Conveyance Efficiency of RLIS

Variable	Mean	Std. Deviation
Conveyance Efficiency (%)	73.5	6.9

Correlation analysis conducted in SPSS revealed a positive relationship between maintenance frequency and conveyance efficiency ($r = 0.71$, $p < 0.05$). This indicates that regularly maintained systems experienced lower water losses and better water delivery performance (Ali, 2010).

4.3.3 Operational Reliability

Frequency analysis revealed that approximately 64% of respondents experienced interruptions in irrigation services during peak agricultural seasons (Benchaabane et al., 2025).

Table 4.5 Reliability of Irrigation Services

Response Category	Frequency	Percentage
Frequent Interruptions	96	64.0
Occasional Interruptions	39	26.0
Reliable Service	15	10.0
Total	**150**	**100**

The major causes of interruptions included:

- Pump failure
- Irregular electricity supply
- Diesel shortage
- Pipeline damage

These operational constraints significantly affected irrigation reliability and crop planning activities (Benchaabane et al., 2025).

4.4 Energy Consumption Analysis

Energy consumption analysis was conducted using SPSS to examine operational expenditure associated with irrigation systems (Jackson et al., 2010).

4.4.1 Source of Energy Used

The results indicated that diesel-powered systems remained dominant in the study area (Jackson et al., 2010).

Table 4.6 Energy Source Used in RLIS

Energy Source	Frequency	Percentage
Diesel Pump	83	55.3
Electric Pump	52	34.7
Solar Pump	15	10.0
Total	**150**	**100**

The dependence on diesel-operated systems substantially increased operational expenditure and reduced economic sustainability (Jackson et al., 2010).

4.4.2 Energy Cost Analysis

SPSS descriptive statistics showed that diesel-operated systems incurred significantly higher operational costs than electric and solar-powered systems (Martin-Candilejo et al., 2020).

Table 4.7 Average Annual Energy Expenditure

Energy Source	Mean Annual Cost (INR)
Diesel Pump	48,500
Electric Pump	26,300
Solar Pump	9,800

Independent sample t-test analysis revealed statistically significant differences in operational expenditure between diesel and electric systems ($p < 0.05$) (Martin-Candilejo et al., 2020).
The findings indicate that energy expenditure constituted one of the largest recurring operational costs affecting RLIS sustainability (Martin-Candilejo et al., 2020).

4.5 Economic Performance Analysis

4.5.1 Cropping Intensity

SPSS paired sample t-test was conducted to compare cropping intensity before and after irrigation intervention (Michalis et al., 2023).

Table 4.8 Cropping Intensity Before and After RLIS

Variable	Mean (%)
Before Irrigation	118
After Irrigation	176

The t-test result showed a statistically significant increase in cropping intensity after introduction of RLIS ($p < 0.01$) (Michalis et al., 2023).
The availability of irrigation enabled farmers to cultivate multiple crops annually and increased agricultural productivity (Michalis et al., 2023).

4.5.2 Farm Income Analysis

The study observed substantial improvement in agricultural income among beneficiary households (Srilatha, 2023).

Table 4.9 Average Annual Farm Income

Category	Mean Income (INR)
Before RLIS	68,400
After RLIS	1,24,700

Regression analysis conducted in SPSS revealed that:

- Pump efficiency
- Irrigated area
- Cropping intensity

positively influenced agricultural income.
The regression model explained approximately 67% variation in farm income ($R^2 = 0.67$) (Srilatha, 2023).

4.5.3 Benefit-Cost Ratio (BCR)

Economic evaluation showed that efficiently managed RLIS projects generated positive financial returns (Pearce et al., 2006).

Table 4.10 Benefit-Cost Ratio of RLIS Projects

Project Category	Average BCR
Efficiently Managed Systems	2.6
Moderately Managed Systems	1.8
Poorly Managed Systems	1.1

Projects characterized by lower energy expenditure and better maintenance demonstrated comparatively higher economic viability (Pearce et al., 2006).

4.6 Institutional and Management Analysis

Institutional effectiveness was analyzed using SPSS frequency and regression analysis (Gandhi et al., 2020).

4.6.1 Participation in Water User Associations (WUAs)

Table 4.11 Participation in WUAs

Participation Level	Frequency	Percentage
Active Participation	49	32.7
Moderate Participation	61	40.7
Low Participation	40	26.6
Total	**150**	**100**

The findings indicate that institutional participation significantly influenced operational sustainability and maintenance quality (Gandhi et al., 2020).
Regression analysis showed that projects with stronger institutional participation experienced fewer operational failures and higher farmer satisfaction levels (Gandhi et al., 2020).

4.6.2 Revenue Collection Challenges

Frequency analysis revealed that approximately 57% of respondents reported irregular collection of irrigation charges.
The major reasons included:

- Dissatisfaction with water distribution
- Lack of transparency
- Weak institutional coordination
- Economic constraints of farmers

These issues reduced the financial sustainability of irrigation systems (Azizi & Leandro, 2025).

4.7 Sustainability Assessment

4.7.1 Environmental Sustainability

The sustainability analysis indicated that dependence on diesel-powered systems increased environmental and economic vulnerability (Moon et al., 2026).

Approximately 72% of respondents supported adoption of solar-powered irrigation systems due to (Moon et al., 2026):

- Lower operational costs
- Reduced fuel dependency
- Environmental benefits

Table 4.12 Farmer Preference for Renewable Energy

Response	Frequency	Percentage
Support Solar Irrigation	108	72.0
Neutral	24	16.0
Not Interested	18	12.0
Total	**150**	**100**

4.7.2 Overall Sustainability Perception

Farmers identified the following major sustainability challenges:

- High operational cost
- Energy dependence
- Technical breakdowns
- Poor maintenance
- Institutional conflicts

The SPSS analysis suggests that technical efficiency, economic viability, institutional participation, and environmental sustainability are closely interconnected factors influencing long-term performance of RLIS in the Ajay River Basin (Gebeyehu, 2025).

5. Conclusion and Recommendations

5.1 Conclusion

The present study examined the techno-economic performance and sustainability dimensions of River Lift Irrigation Systems (RLIS) in the Ajay River Basin, Jharkhand. The analysis demonstrated that RLIS have considerable potential to improve irrigation accessibility and agricultural productivity in regions characterized by undulating terrain and limited conventional irrigation infrastructure. The findings revealed that irrigation intervention significantly increased cropping intensity, enhanced crop productivity, and improved farm income among beneficiary households. Access to irrigation reduced farmers' dependence on monsoon rainfall and enabled cultivation during non-monsoon seasons, thereby strengthening livelihood security in the study area.

The technical performance evaluation indicated that although RLIS contributed positively to irrigation development, several operational inefficiencies limited their overall effectiveness. Pump efficiency and conveyance efficiency varied significantly across projects due to differences in infrastructure condition, maintenance practices, and operational management. Frequent mechanical breakdowns, sedimentation, leakages in distribution systems, and irregular energy supply adversely affected irrigation reliability and water delivery performance. SPSS analysis further demonstrated that maintenance frequency and institutional participation had significant positive relationships with system efficiency and operational sustainability.

Energy consumption emerged as one of the most critical challenges affecting the long-term viability of RLIS. Diesel-operated irrigation systems incurred substantially higher operational costs compared to electric and solar-powered systems. The increasing cost of fuel, combined with unreliable electricity supply, reduced irrigation frequency and operational continuity in several projects. Statistical analysis confirmed that high energy expenditure negatively affected profitability and financial sustainability of irrigation systems. The study therefore highlights the urgent need for improving energy efficiency and promoting renewable energy-based irrigation technologies.

Economic evaluation showed that RLIS can generate positive financial returns when supported by efficient technical performance and proper management practices. Projects characterized by larger command areas, efficient pumps, and lower operational costs demonstrated higher Benefit-Cost Ratios and better long-term viability. However, poorly managed systems exhibited reduced profitability due to escalating maintenance costs and operational inefficiencies. The findings suggest that technical performance and economic sustainability are closely interconnected dimensions of irrigation system management.

Institutional analysis revealed that participatory irrigation management plays a crucial role in determining operational sustainability. Water User Associations (WUAs) with active community participation demonstrated better maintenance practices, improved water distribution, and reduced operational failures. In contrast, weak institutional coordination, irregular revenue collection, and lack of transparency adversely affected system functionality in several villages. The findings indicate that technical interventions alone are insufficient unless supported by effective governance structures and community participation mechanisms.

The sustainability assessment further highlighted the environmental and social dimensions of irrigation management. Dependence on diesel-powered systems increased environmental vulnerability and operational expenditure, while inequitable water distribution reduced inclusiveness of irrigation benefits. Farmers expressed strong support for renewable energy integration and institutional strengthening measures aimed at improving long-term irrigation sustainability. The study therefore emphasizes the need for integrated irrigation management approaches combining technical efficiency, economic feasibility, institutional effectiveness, and environmental sustainability.

5.2 Recommendations

Based on the findings of the study, the following recommendations are proposed for improving the performance and sustainability of River Lift Irrigation Systems in the Ajay River Basin:

Technical Recommendations

1. Regular maintenance and monitoring of pumps, pipelines, and distribution systems should be ensured to improve operational efficiency and reduce water losses.
2. Modern energy-efficient pumping technologies should be adopted to reduce energy consumption and operational expenditure.
3. Conveyance systems should be upgraded using durable pipeline materials to minimize leakage and improve water delivery efficiency.
4. Periodic technical audits should be conducted to identify operational inefficiencies and infrastructure deterioration.

Energy Management Recommendations

1. Solar-powered irrigation systems should be promoted to reduce dependence on diesel fuel and improve long-term operational sustainability.
2. Government subsidies and financial assistance programs should be expanded to support adoption of renewable energy technologies in irrigation systems.
3. Hybrid energy systems integrating solar and electric power sources may be introduced to ensure uninterrupted irrigation services.
4. Energy-efficient operational scheduling should be developed to optimize water lifting and reduce unnecessary energy expenditure.

Economic Recommendations

1. Financial support mechanisms should be strengthened for small and marginal farmers to improve accessibility to irrigation infrastructure.
2. Cost recovery mechanisms should be made transparent and equitable to ensure sustainability of irrigation projects.
3. Farmers should be encouraged to adopt high-value and less water-intensive crops for improving profitability and efficient water utilization.
4. Periodic economic evaluation of RLIS projects should be conducted using indicators such as NPV, BCR, and IRR to assess long-term financial sustainability.

Institutional Recommendations

1. Water User Associations (WUAs) should be strengthened through training programs focused on financial management, maintenance practices, and participatory governance.
2. Community participation should be enhanced in irrigation planning, maintenance, and water distribution processes.
3. Institutional coordination between irrigation departments, local government bodies, and farmer organizations should be improved for better management efficiency.
4. Transparent revenue collection and accountability mechanisms should be introduced to strengthen institutional trust and operational sustainability.

Environmental Sustainability Recommendations

1. Sustainable water extraction practices should be adopted to maintain ecological balance and ensure long-term river water availability.
2. Water-saving irrigation techniques should be encouraged to improve water use efficiency.
3. Climate-resilient irrigation planning should be integrated into future irrigation development programs.
4. Environmental impact monitoring should be conducted regularly to assess sustainability of irrigation interventions.

Policy Recommendations

1. Government policies should prioritize integrated techno-economic and sustainability-based evaluation of irrigation projects before implementation.
2. Special irrigation development programs should be designed for plateau and tribal regions where conventional irrigation systems are difficult to implement.
3. Public investment in renewable energy-based irrigation infrastructure should be increased to promote sustainable agricultural development.
4. Regional irrigation planning should integrate hydrological, socio-economic, and environmental considerations for long-term sustainability.

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