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Modernization of Submersible Pump Designs for Sustainable Irrigation: A Bibliometric and Experimental Contribution to Sustainable Development Goals (SDGs)

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ABSTRACT

Modernization of submersible pump design is essential to improve the sustainability and operational reliability of irrigation systems. This study combines bibliometric analysis and experimental evaluation to address performance degradation due to cavitation, sedimentation, and mechanical wear. Bibliometric results demonstrate growing global interest in energy-efficient and reliable irrigation technologies. Laboratory tests evaluated pump efficiency, hydraulic performance, and component wear. Physical inspections showed impeller erosion and casing degradation significantly reduced hydraulic stability, as sediment-laden flow and cavitation accelerated material loss. To predict pump life, a vibration-based reliability model was developed for early detection of deterioration and condition-based maintenance. This design innovation enhances irrigation efficiency and energy use while extending pump life by reducing wear and instability. The integrated approach offers a practical framework for sustaining irrigation infrastructure amid rising agricultural and environmental demands. The results contribute to several Sustainable Development Goals, especially in water resource management, clean energy, food security, and climate resilience.

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1. INTRODUCTION

Efficient water resource management is a critical component for enhancing global agricultural productivity and ensuring food security, particularly in arid and semi-arid regions. In the development strategies of Central Asian countries, improving the operation of water management facilities, enhancing the efficiency of irrigation projects, and strengthening scientific research in this field remain primary priorities [1, 2]. The operation of mechanical water-lifting systems presents multiple challenges, including rapid equipment wear, shortened service life, and excessive energy consumption, which are primarily caused by waterjet-induced impeller wear, declining pressure characteristics, and deteriorating system conditions.

Submersible pumps play a central role in sustaining irrigation systems; however, their operational reliability is frequently compromised by cavitation damage and sediment accumulation, thereby limiting continuous operation duration. The growing significance of submersible pump reliability has attracted extensive research interest focused on enhancing pump performance and extending service life [3, 4].

Vertical drainage systems have demonstrated the ability to stabilize water-salt regimes on irrigated lands while conserving irrigation water by regulating its use [5]. Vertical drainage offers superior land use efficiency compared to horizontal systems, contributing significantly to water-saving initiatives. Moreover, these systems support broader objectives of sustainable agricultural practices, which are essential for countries facing increasing water scarcity.

In recent years, bibliometric analyses have highlighted a growing global research interest in modernizing irrigation pumping systems, emphasizing the importance of integrated approaches that combine technological innovation and sustainability principles [6, 7]. However, studies that directly integrate bibliometric findings with experimental validation in the context of submersible pump modernization remain scarce.

This study introduces a novel integration of bibliometric analysis and experimental validation to optimize submersible pump designs for sustainable irrigation. Bibliometric is effective for understanding current research as reported elsewhere [6, 7].

The research provides new insights into vibration-based reliability assessment, sediment management, and cavitation mitigation, as these improvements minimize operational failures, extend equipment lifespan, and enhance resource efficiency. Furthermore, the study explicitly aligns its contributions with several United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 7 (Affordable and Clean Energy). Detailed information regarding SDGs is reported elsewhere [8-10]. The outcomes aim to support sustainable agricultural water management, particularly in regions confronting environmental and resource challenges.

2. LITERATURE REVIEW

2.1. Submersible Pumps in Irrigation Systems

The effective operation of irrigation systems largely depends on the performance of submersible pumps, which are widely employed to lift groundwater in both vertical and horizontal drainage systems. These pumps are vital for maintaining water-salt regimes and supporting agricultural productivity, especially in arid and semi-arid regions [1, 2]. Vertical drainage systems, in particular, have demonstrated superior efficiency compared to horizontal drainage because they offer better water regulation and higher land-use efficiency [5].

2.2. Efficiency, Wear, and Reliability Factors

Submersible pump performance is often limited by mechanical wear, hydraulic losses, cavitation, and sediment accumulation. Among these, impeller waterjet wear has been identified as one of the most significant contributors to performance degradation. Other components, such as spiral branches, gate valves, support units, and bearings, are also prone to operational wear, leading to frequent system failures if not addressed properly [3, 4].

Cavitation is particularly destructive because it causes structural degradation in the impeller chamber, substantially reducing the pump's operational life. Wear indicators such as vibration levels, sedimentation rates, and pressure fluctuations have become essential parameters for assessing pump reliability [11, 12]. Predictive maintenance using vibration monitoring has shown promise in improving pump longevity and preventing unplanned outages [13].

2.3. Current Challenges in Sustainable Irrigation

Sustainable irrigation requires not only reliable pump operation but also energy efficiency and effective water conservation. Failures in pump systems contribute directly to unnecessary energy consumption and water loss, negatively affecting both economic viability and environmental sustainability [9]. The increasing global demand for sustainable solutions has driven research efforts toward innovative design improvements and advanced monitoring systems [14, 15].

Detailed technical principles related to pump design and testing procedures are discussed comprehensively by Chebaevsky & Vishnevsky in their book published in 2000 regarding "Design of pumping stations and testing of pumping units". However, despite the rising volume of research, bibliometric analyses reveal that experimental studies combining technical innovation, failure analysis, and sustainability perspectives are still limited. This research gap underscores the need for studies that systematically integrate bibliometric insights with experimental validation to inform the modernization of submersible pump systems.

3. METHODS

This study employed a combination of bibliometric analysis, theoretical modeling, expert evaluation, and experimental testing to assess and improve the technical condition of submersible pump systems used in irrigation. The bibliometric analysis was conducted to identify current global research trends and gaps related to pump modernization and sustainable irrigation technologies. Detailed procedures for conducting bibliometric analysis are explained elsewhere [16-18].

The technical analysis involved the generalization and evaluation of operational data from irrigation systems, including both classical and modern design methods. Indicators related to the technical condition of pumping systems, such as hydraulic efficiency, operational reliability, and component wear, were determined based on standardized evaluation criteria [9].

To evaluate system performance, efficiency measurements were conducted for both lined and unlined irrigation canals. The technical condition of key hydraulic structures was assessed based on normative values of hydraulic efficiency (ηs), system reliability (Rts), and wear indicators (Iws), following established methodologies [11].

Experimental tests were performed using submersible pumps installed on dedicated test benches. The measurement system included specialized instruments capable of capturing flow rate, head, rotational speed, efficiency, power consumption, and vibration levels under controlled laboratory conditions. These tests allowed verification of pump performance under varying operational scenarios, including conditions approaching cavitation wear [13].

In addition, the experimental design incorporated vibration monitoring to assess early-stage failures, mechanical imbalance, and hydrodynamic instabilities. The evaluation of vibration parameters across multiple frequency ranges provided detailed insights into the operational condition and remaining service life of the submersible pump units [12].

All measurements were performed using standardized instruments with traceable calibration to ensure accuracy and reproducibility of results under both laboratory and simulated field conditions.

4. RESULTS AND DISCUSSION

4.1. Bibliometric Analysis of Research Trends

To understand the current global research landscape on submersible pumps for irrigation systems, a bibliometric analysis was conducted using the Scopus database. The search utilized the query TITLE-ABS-KEY ("pump" AND "irrigation") and retrieved a total of 4,887 documents published between 1935 and 2024.

As shown in **Figure 1**, there has been a significant increase in research output over the past decade. In 2016, the number of publications was relatively modest at 174, but steadily increased to 186 in 2017 and reached 377 publications by 2024. This clear upward trajectory highlights the growing global research focus on pump design, irrigation efficiency, and sustainable water resource management.

The increasing number of publications reflects heightened international attention toward developing efficient pumping technologies to address challenges related to water scarcity, energy consumption, and climate change because these issues are becoming increasingly critical in global agricultural sustainability agendas [16-18].

The dominant themes identified in this bibliometric analysis include cavitation mitigation, energy-efficient irrigation, vibration-based monitoring, and predictive maintenance models—topics that directly align with the objectives and contributions of this study.

The results of this bibliometric review further validate the novelty of the present research because integrated studies combining experimental validation with bibliometric insights remain limited. Therefore, this work contributes to addressing an important research gap at the intersection of engineering innovation and sustainable development.

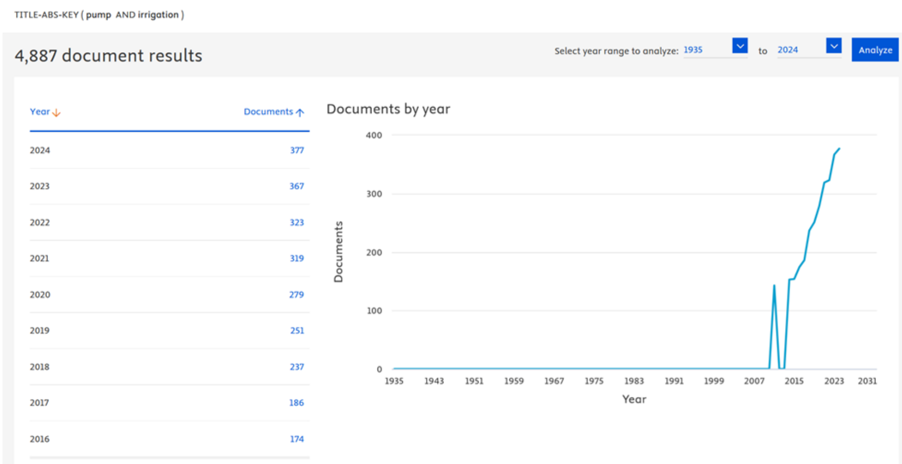

Figure 1. Bibliometric trend of global publications on pump and irrigation (1935–2024), based on Scopus database analysis.

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4.2 Experimental Results and Degradation Analysis

Experimental investigations were conducted to evaluate the operational performance, degradation behavior, and failure mechanisms of submersible pumps used in irrigation systems. The experimental setup is illustrated schematically in **Figure 2**, which details the test configuration, including the swimming pool (1), test unit (2), connecting pipe (3), pressure pipeline (4), valve (5), discharge pipe (6), K 505 set (7), pressure gauge (8), and thermometer (9). The physical installation of the test bench system is shown in **Figure 3**, confirming the controlled laboratory conditions under which all tests were performed.

To ensure that the experimental investigation accurately reflected the range of operating conditions encountered in practical irrigation systems, multiple submersible pump configurations were selected for testing. The ECW pump series includes variations in both flow capacity and head rating, allowing for performance assessment across different hydraulic scenarios. Lower head and higher flow models, such as ECW 12-255-30МКt, represent typical applications for high-volume, shallow-well irrigation, while higher head and lower flow models, such as ECW 10-63-150МКt, simulate conditions where water must be lifted from deeper sources. This variation provides a comprehensive evaluation of pump performance under diverse operational demands, supporting broader applicability of the research findings to real-world irrigation systems.

Performance parameters such as flow rate, total head, rotational speed, unit efficiency, and power consumption were measured for different ECW pump models. The collected data are summarized in **Table 1**, presenting operational variations across multiple test configurations. The measured efficiency ranged between 30% and 61%, depending on pump condition, impeller geometry, hydraulic load, and degradation severity. The highest efficiency was observed in pumps with minimal wear, while lower efficiencies were recorded for pumps experiencing significant cavitation and mechanical wear.

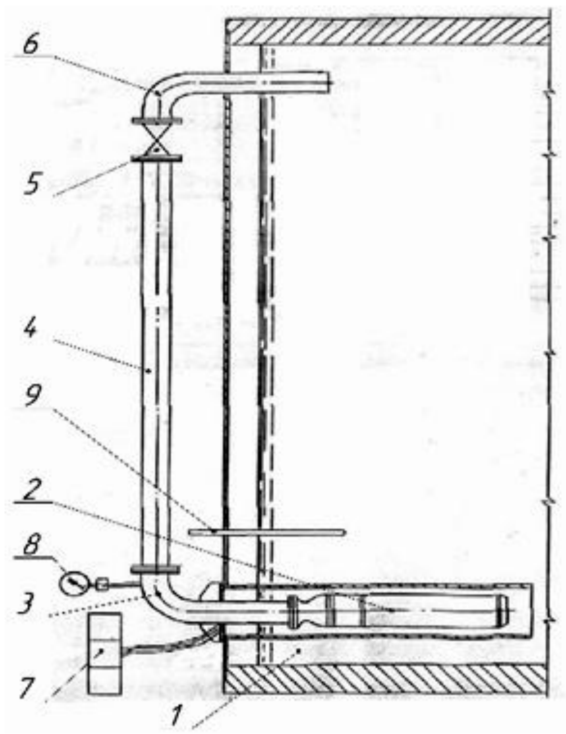

Figure 2. Schematic of test bench system. Note: 1 is the swimming pool; 2 is the unit under test; 3 is the connecting pipe; 4 is the pressure pipeline; 5 is the valve; 6 is the discharge pipe; 7 is the set K 505; 8 is the pressure gauge; 9 is the thermometer.

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Figure 3. Actual photo of test bench system.

Table 1. Experimental Test Results of Submersible Pumps.

Unit Type	Flow Rate (m^3/h)	Head (m)	Rotational Speed (min^{-1})	Efficiency (%)	Power (kW)
ECW 10-63-110MKt	63.0	110.0	2900	60	27.0
ECW 10-63-150MKt	63.0	150.0	2900	61	45.0
ECW 10-120-40MKt	120.0	30.0	2900	52	22.0
ECW 10-160-35MKt	160.0	35.0	2900	35	22.0
ECW 12-255-30MKt	255.0	30.0	2900	30	27.0

Note: unit pump ECW series with detailed types:
(i) ECW 10-63-110MKt = diameter 10, flow rate 63 m^3/h, head 110 m
(ii) ECW 10-63-150MKt = Diameter 10, flow rate 63 m^3/h, head 150 m
(iii) ECW 10-120-40MKt = Diameter 10, flow rate 120 m^3/h, head 40 m
(iv) ECW 10-160-35MKt = Diameter 10, flow rate 160 m^3/h, head 35 m
(v) ECW 12-255-30MKt = Diameter 12, flow rate 255 m^3/h, head 30 m

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After testing, the pumps were disassembled for physical inspection to assess degradation levels. **Figure 4** shows the external condition of the pump unit, where extensive casing wear, corrosion, and shaft degradation are evident after prolonged exposure to sediment-laden water. These structural degradations reduce hydraulic stability and overall system reliability. Internally, severe impeller wear was observed, as depicted in **Figure 5**, which displays cavitation-induced pitting, edge erosion, and blade thinning resulting from continuous high-velocity water flow containing abrasive particles. The combined effects of cavitation and sediment erosion alter the impeller geometry and significantly reduce hydraulic efficiency.

Quantitative assessment of system degradation was performed using wear indicators (Iws). Based on established technical standards [11], wear below 5% indicates normal condition, while values between 15 and 20% reflect satisfactory but degrading conditions. Severe wear above 25% signifies advanced deterioration, requiring immediate maintenance or component replacement to prevent catastrophic failure.

The degradation process directly affects system capacity because wear reduces hydraulic performance and accelerates failure rates. The relationship between system capacity (*Q*), design capacity (*Qd*), and reliability under degraded conditions can be expressed as equation (1):

$$\frac{Q}{Qd} \leq 1 \tag{1}$$

In parallel, the frequency of failure related to siltation can be modeled as equation (2):

$$\omega(t) = \frac{W(t)}{[V]} \tag{2}$$

where *ω(t)* represents the failure flow parameter, *W(t)* is the accumulated sediment volume at time *t*, and *[V]* is the permissible sedimentation volume.

Figure 4. Experimental testing of ECW submersible pumps on dedicated test benches during performance evaluation: Internal view of impeller.

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Figure 5. Experimental testing of ECW submersible pumps on dedicated test benches during performance evaluation: External view of pump.

The combined findings demonstrate that both hydraulic efficiency losses and sediment-induced wear strongly influence system degradation because they simultaneously reduce performance and shorten service life. Therefore, continuous monitoring and modernization strategies focusing on sediment management, impeller design optimization, and cavitation control are essential for sustaining long-term pump reliability in irrigation systems.

4.3. Reliability Modeling and Vibration-Based Lifetime Prediction

In addition to performance testing and physical degradation analysis, this study incorporated reliability modeling to predict the remaining service life of submersible pumps based on vibration monitoring data. Operational experience has shown that as wear progresses, vibration levels increase due to imbalances, shaft misalignment, bearing deterioration, and hydrodynamic instabilities [13].

Vibration measurements were taken across multiple frequency bands to capture mechanical and hydraulic abnormalities during pump operation. Increased impeller blade angle was found to elevate vibration amplitudes by approximately 10 dB in the first frequency range, 8 dB in the second, and 6 dB in the third range. Radial and vertical vibrations were strongly influenced by shaft-line misalignment, while hydrodynamic imbalance elevated tangential vibrations. Bearing wear contributed primarily to radial vibration growth [11, 12].

Because vibration amplitude directly reflects the internal condition of the pump, a predictive model was established to estimate the remaining operational life based on observed vibration growth. The model is mathematically expressed as equation (3):

$$T = \frac{1}{Kf}\left(\frac{W}{B0}\right)^{\frac{1}{\beta}} \quad (3)$$

where *T* is the remaining service life of the pump, *Kf* is the detection frequency coefficient of increased vibration (typically 0.80 - 0.95), *β* is the exponent representing the rate of vibration growth over time, *B0* is the initial vibration level, and *W* is the overall vibration level at the time of observation.

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This model allows for real-time calculation of remaining service life, enabling operators to schedule predictive maintenance interventions before severe failures occur. Because the model integrates real-time vibration data, it offers a more accurate and dynamic estimation of system reliability compared to conventional time-based maintenance schedules.

The application of vibration-based lifetime prediction provides a significant advancement in condition-based maintenance strategies for irrigation pumping systems. Early detection of abnormal vibration patterns allows corrective actions to be implemented before catastrophic breakdowns, reducing downtime, minimizing repair costs, and extending pump lifespan. Ultimately, this approach supports both operational efficiency and long-term sustainability of irrigation infrastructures.

4.4. Contribution to Sustainable Development Goals (SDGs)

The findings of this study directly support multiple United Nations Sustainable Development Goals (SDGs) by improving the efficiency, reliability, and sustainability of irrigation pumping systems. The proposed modernization of submersible pump designs contributes to SDG 6 (Clean Water and Sanitation) because it enhances water-use efficiency by minimizing hydraulic losses, preventing unnecessary leakage, and optimizing water distribution across irrigated farmlands. The experimental evaluation demonstrates that system efficiency deteriorates due to cavitation, sediment-induced wear, and mechanical degradation. Addressing these failure mechanisms through design improvements and predictive maintenance extends pump service life and operational stability. Consequently, energy consumption is significantly reduced because pumps operate closer to their design efficiency throughout their service period, directly supporting SDG 7 (Affordable and Clean Energy). By improving water availability and irrigation performance, the proposed innovations also contribute to SDG 2 (Zero Hunger), especially in regions experiencing water scarcity and increased agricultural demand. The bibliometric analysis further highlights growing global research efforts targeting technological innovation in irrigation infrastructure, aligning with SDG 9 (Industry, Innovation, and Infrastructure) [16-18]. Moreover, by reducing resource waste, lowering energy demand, and enhancing operational reliability under variable environmental conditions, the proposed system advances SDG 13 (Climate Action). These combined improvements provide a practical framework for enhancing irrigation system sustainability and resilience under increasing pressures of climate variability and global food security demands. Finally, this study extends the SDG discussion following previous investigations related to educational, environmental, and technological SDG topics reported elsewhere [19-25].

5. CONCLUSION

This study successfully modernized submersible pump designs by integrating bibliometric analysis with experimental validation. The investigation addressed key degradation mechanisms such as cavitation wear, sediment-induced erosion, and mechanical instability.

Vibration-based reliability modeling enabled accurate lifetime prediction and supported condition-based maintenance. These innovations improve irrigation efficiency, reduce energy consumption, and enhance long-term system sustainability because they directly mitigate failure progression. Overall, the outcomes contribute significantly to global efforts in achieving multiple SDGs related to water, energy, agriculture, and climate resilience.

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6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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