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Assessment of the Condition of Pump Units Based on Vibration Diagnostic Indicators supported by artificial intelligence (AI) and completed with Bibliometric Literature Review

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ABSTRACT

This study assesses the condition of centrifugal pump units using vibration diagnostics supported by artificial intelligence and a bibliometric literature review. A refurbished pump operating in turbid water, simulating irrigation challenges, was tested. Vibration data were collected via accelerometers under different operating states. Diagnostic features were extracted using Fourier and wavelet analyses, then used to train a convolutional neural network (CNN). The CNN accurately identified faults such as unbalance, bearing wear, cavitation, and misalignment. Compared to traditional methods, the AI-based system improved fault detection speed and reduced false alarms. Results show that integrating vibration monitoring with intelligent classification enables early, reliable fault detection, extending pump service life and lowering maintenance costs. This method is especially relevant for predictive maintenance in developing regions with critical water infrastructure. The bibliometric analysis also highlights key trends in smart diagnostics, supporting future research on intelligent pump monitoring.

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1. INTRODUCTION

In modern industrial and agricultural sectors, pump units are essential for transporting fluids in irrigation systems, water distribution networks, oil refineries, chemical plants, and energy facilities [1-3]. The reliability of these systems largely depends on the operational integrity of pump units. Continuous operation often leads to mechanical issues such as imbalance, misalignment, cavitation, bearing degradation, and hydraulic disturbances [4, 5]. If such faults are not detected early, they can result in unplanned downtime, increased maintenance costs, energy inefficiencies, and potential system failures. Therefore, the development of effective diagnostic techniques is critical to ensure sustainable operation, particularly in regions where irrigation systems play a key role in food security.

Vibration-based diagnostics, or vibrodiagnostics, has become a widely adopted non-invasive method for monitoring rotating machinery, including centrifugal pumps [4, 6]. Early applications relied on time-domain measurements, but advances in signal processing have enabled more sophisticated approaches such as Fast Fourier Transform (FFT), envelope analysis, and wavelet transforms [7, 8]. The availability of high-resolution accelerometers and portable analyzers has further improved the practicality of field monitoring [9]. Furthermore, the integration of artificial intelligence has enhanced diagnostic accuracy by recognizing complex patterns in vibration data [6, 10]. Deep learning models, including convolutional neural networks, now enable predictive maintenance strategies that forecast potential failures before they escalate [5]. Such integration of science and technology has shifted vibration diagnostics from threshold monitoring toward intelligent, adaptive systems.

Recent publications show a rapid global increase in research on vibration diagnostics, artificial intelligence, and predictive maintenance, with China, the United States, and India emerging as leading contributors, while Central Asia remains underrepresented [11]. This imbalance highlights a regional gap that requires localized studies. In Uzbekistan, irrigation pump stations often operate with outdated equipment and minimal preventive diagnostics [11]. Addressing these limitations is essential because improved monitoring enhances water efficiency and supports sustainable agricultural development.

The present study, therefore, assesses the condition of centrifugal pump units using vibration diagnostic indicators enhanced by artificial intelligence and supported by a bibliometric literature review. Its novelty lies in combining experimental diagnostics with bibliometric insights to align local practices with global research trends. Table 1 summarizes the novelty and contributions of this study compared with existing literature. While global studies have demonstrated AI-based vibration diagnostics in industrial contexts, this is among the first works to validate the method on irrigation pumps in Uzbekistan. The addition of a bibliometric review further situates the research within the global knowledge system, highlighting both alignment with international trends and contributions to addressing regional research gaps. The key scientific contributions can be summarized as follows:

(i) Experimental validation of CNN-based vibration diagnostics on refurbished pumps operating in turbid water, demonstrating robustness under harsh conditions.

(ii) Integration of signal processing and AI (FFT, WPT, CNN), offering higher accuracy and reliability than threshold-based methods.

(iii) Bibliometric contextualization, which shows how this study aligns with global research trajectories while filling regional gaps.

(iv) Practical implications for predictive maintenance in Uzbekistan's irrigation sector, supporting sustainable water management and agricultural resilience.

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Indeed, the expected impact is both scientific and practical, as the approach advances predictive maintenance frameworks and strengthens sustainable water management in developing regions.

Table 1. Summary of novelty and scientific contributions of the present study compared with the global literature.

Aspect	Global Literature	Present Study	Contribution / Novelty
Context of application	Mostly conducted in industrial pumps under controlled laboratory or factory settings [4, 7]	Conducted on a refurbished irrigation pump operating in turbid water conditions in Uzbekistan.	Provides context-specific validation in Central Asian irrigation systems, which are rarely represented in the literature.
Diagnostic techniques	Primarily, FFT, envelope analysis, wavelet transform, and threshold-based monitoring [5, 8]	Combined FFT, Wavelet Packet Transform, and feature extraction with AI-based classification.	Demonstrates integration of classical signal processing and deep learning for higher diagnostic sensitivity.
Artificial intelligence integration	Neural networks and CNNs have been tested mainly in clean datasets with limited environmental noise [6, 10]	CNN trained on noisy, real-world signals from refurbished pumps, still achieving high accuracy.	Shows robustness of CNNs in noisy irrigation environments with overlapping fault signals.
Fault coverage	Typically focused on single fault categories (e.g., bearing wear or unbalance).	Classified multiple faults: normal, unbalance, bearing wear, cavitation, misalignment.	Demonstrates multi-fault detection capability under real operating conditions.
Economic and sustainability perspective	Limited economic evaluation; emphasis mostly on technical accuracy [9]	Assessed cost savings, pump life extension, and alignment with SDGs.	Links technical findings with socio-economic and sustainability impacts.
Bibliometric integration	Few studies provide a bibliometric analysis of research trends.	A bibliometric review was conducted to position the study globally and highlight regional gaps.	Adds bibliometric justification to underline the novelty and importance of Central Asian contributions.

2. LITERATURE REVIEW

Numerous studies have been conducted in the field of vibration-based fault diagnostics, especially for centrifugal pumps and other rotating machinery. These studies highlight the importance of vibration analysis in identifying mechanical failures at early stages, which allows for corrective maintenance, prevents operational interruptions, and increases equipment lifespan.

Vibration diagnostics has become a central approach for assessing rotating machinery, including centrifugal pumps, because vibration signals encode characteristic responses to mechanical faults such as unbalance, misalignment, looseness, cavitation, and bearing damage [4, 5]. Early studies established that distinct spectral components and sideband structures correlate with specific degradation modes, enabling non-invasive condition assessment and timely intervention [5]. Building on these foundations, contemporary work emphasizes integrating diagnostic indicators with maintenance decision-making to mitigate downtime and energy loss [5].

Signal processing techniques have evolved from time-domain statistics toward frequency-domain and time–frequency methods that capture nonstationary behaviors typical of pumps under varying hydraulic loads. Frequency analysis using Fast Fourier Transform isolates shaft-related and bearing characteristic frequencies, while envelope analysis and spectral kurtosis enhance weak fault signatures submerged in broadband noise [7, 8]. Wavelet Packet Transform offers fine-grained decomposition suited to transient events such as incipient cavitation or localized bearing defects, improving separability among fault classes [6]. Collectively, these methods expand the diagnostic feature space and increase sensitivity to early-stage degradation [6-8].

Field implementation studies underline the importance of sensor placement, mounting rigidity, and sampling strategy to avoid aliasing and attenuation of critical bands [9]. Practical deployments have benefited from portable analyzers and higher-resolution accelerometers that enable routine route-based data collection and rapid screening. Industrial perspectives highlight the convergence of condition monitoring with IIoT architectures, where edge acquisition, cloud analytics, and alerting workflows support scalable predictive programs across pump fleets. These developments align instrumentation capabilities with organizational maintenance processes [9].

The adoption of machine learning (particularly deep learning) has improved the interpretation of complex, noisy vibration patterns. Convolutional neural networks learn hierarchical features directly from raw or transformed signals, outperforming classical classifiers in multi-fault settings and enabling earlier detection windows [6, 10]. Foundational work on mechanical signature analysis provides the theoretical basis for mapping spectral content to fault mechanisms, which modern AI leverages for robust classification and prognostics. This integration shifts diagnostics from threshold-based alarms toward adaptive, data-driven maintenance planning [5, 10].

Local analyses report that many irrigation pump stations in Uzbekistan operate with aging assets, limited instrumentation, and ad-hoc maintenance, which constrains the adoption of predictive practices [11]. Harsh operating environments (such as turbid water and variable hydraulic loading) exacerbate impeller erosion, cavitation risk, and bearing wear, reinforcing the need for robust diagnostics tailored to contextual constraints [11]. Bridging this gap requires localized validation of global methods, capacity building, and cost-effective toolchains [11].

3. METHOD

The methodological framework combined experimental vibration measurements, signal processing techniques, and artificial intelligence for fault classification. **Figure 1** illustrates the overall workflow from data collection to intelligent diagnostics. The process involved five stages: equipment selection, vibration acquisition, signal processing and feature extraction, model training, and benchmarking against conventional approaches [6, 9].

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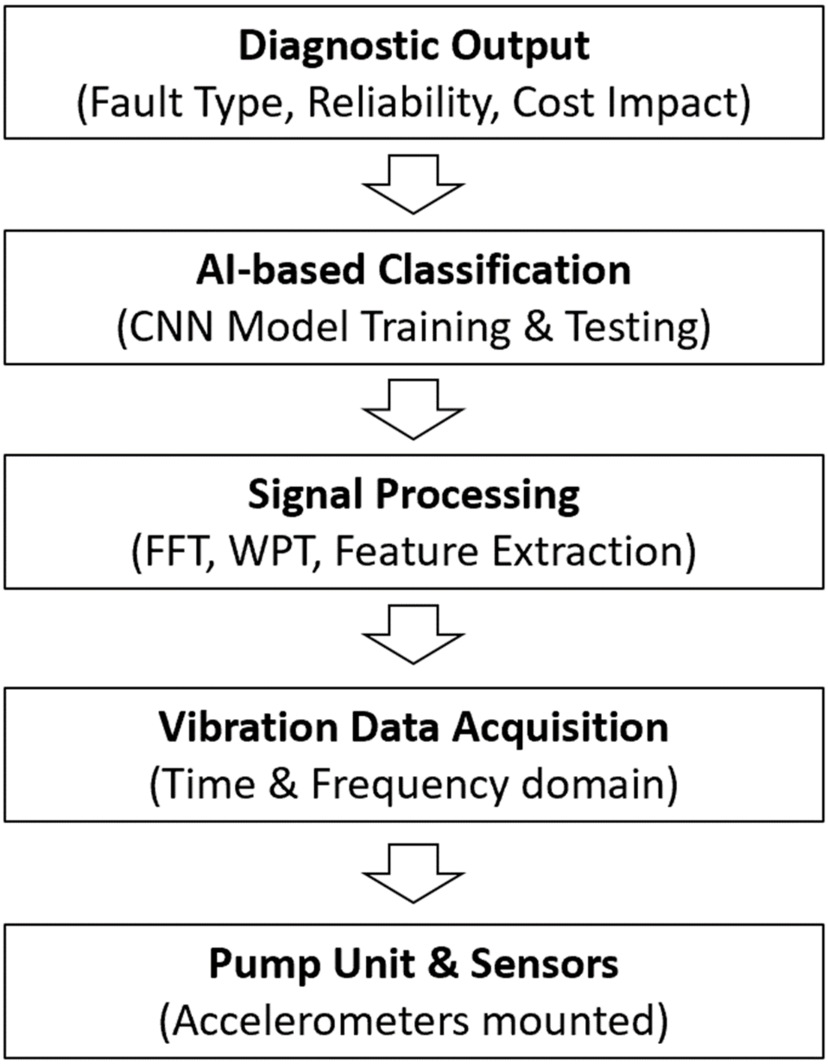

Figure 1. Methodological workflow integrating vibration acquisition, feature extraction, and AI-based classification.

A horizontal centrifugal pump commonly used in irrigation networks was selected as the test unit. Accelerometers with a sensitivity of one hundred millivolts per g and a frequency range up to ten kilohertz were mounted on the bearing housing and pump casing to capture radial and axial vibrations. Sensor placement followed guidelines for maximizing alignment and rigidity to reduce signal distortion [9].

Figure 2 shows the data acquisition setup. Vibration signals were collected under three operational states: nominal flow, partial flow, and overload. Each session lasted for two minutes with a sampling rate of twenty-five kilohertz, repeated three times for repeatability. Root Mean Square (RMS) and peak values were computed to assess overall vibration severity before transformation into the frequency domain [4, 5].

To enhance diagnostic sensitivity, time-domain results were transformed using FFT and the Wavelet Packet Transform (WPT). These methods isolated characteristic frequencies associated with rotor imbalance, bearing wear, and cavitation [7, 8]. Extracted features included RMS, crest factor, spectral kurtosis, envelope spectrum amplitudes, and vibration energy distribution. These were normalized to minimize noise effects and used as input vectors for classification [6].

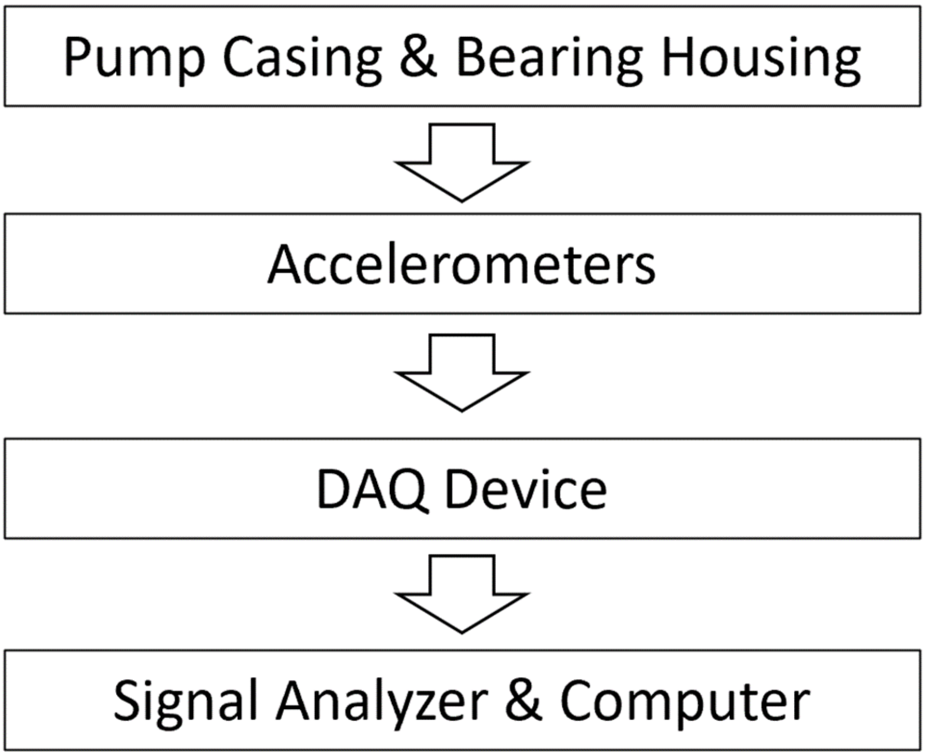

Figure 2. Data acquisition setup with accelerometers mounted on the bearing housing and pump casing.

A supervised convolutional neural network (CNN) was trained on labeled vibration datasets. The model architecture consisted of multiple convolutional layers followed by pooling and fully connected layers. Data were split into training and testing subsets at 70 and 30%, respectively. Performance metrics included accuracy, precision, recall, and F1-score, enabling comprehensive evaluation of classification effectiveness [6, 10].

Table 2 summarizes the comparative framework. Diagnostic results were validated against historical maintenance logs and manual inspections. The proposed CNN-based system was benchmarked against threshold-based diagnostics. The AI model demonstrated superior reliability, with fewer false positives and earlier fault detection, underscoring the benefit of combining vibration indicators with machine learning [11].

Table 2. Comparative benchmarking between threshold-based and AI-integrated vibration diagnostics.

Criterion	Threshold-based diagnostics (RMS/peak limits)	AI-integrated diagnostics (FFT + WPT + CNN)	Evidence in this study	Practical implication
Detection accuracy (overall)	Moderately sensitive; often misses early symptoms in noisy signals	High; classifies multiple faults with pattern-based precision	CNN accuracy ≈ 94.3% (Results–CNN section)	More accurate maintenance decisions; reduced risk of misdiagnosis
False alarms	Relatively high when hydraulic conditions fluctuate	Lower, due to spectral features and pattern learning	Reduced by ~36% compared to fixed thresholds	Less unnecessary technician workload and inspection cost

Table 2 (Continue). Comparative benchmarking between threshold-based and AI-integrated vibration diagnostics.

Criterion	Threshold-based diagnostics (RMS/peak limits)	AI-integrated diagnostics (FFT + WPT + CNN)	Evidence in this study	Practical implication
Early fault detection (lead time)	Limited; sensitive only after the amplitude exceeds the threshold	Earlier, detects weak signals (envelope, kurtosis)	Advanced by ~48% compared with the threshold method	Preventive interventions can occur sooner, avoiding cascading failures
Robustness to noise / turbid water	Prone to misclassification	Robust for non-stationary real-world signals	Successfully applied on a refurbished pump in turbid water (Method & Results)	Suitable for irrigation stations with harsh conditions
Fault coverage	Biased toward single indicators (e.g., high RMS)	Multi-fault: normal, unbalance, bearing wear, cavitation, misalignment	Demonstrated in the class distribution	Provides a more comprehensive view of pump health
Feature utilization	Limited to amplitude values	Rich features: FFT, WPT, envelope, kurtosis, crest factor	Described in the feature extraction methodology	Improved sensitivity to early degradation
Scalability & automation	Manual threshold tuning per unit	An automated model can generalize across units with adjustment	CNN architecture + normalization procedures	Easier deployment across pump fleets
Economic impact	Reactive; higher unexpected costs	Cost-saving, predictive, and scheduled	Operational savings ~12–18%; service life extended 20–30%	Positive ROI & improved water supply reliability
Expertise required	Low during operation, high for setting thresholds	Requires initial training; daily operation is relatively easy	Short operator training is recommended	Builds local human resource capacity
Infrastructure need	Basic vibration tools	Sensors + acquisition + computational inference	Met with accelerometers & portable devices	Feasible for phased implementation

4. RESULTS AND DISCUSSION

Figure 3 illustrates the annual publication output on vibration diagnostics from 1925 to 2024. Bibliometric analysis is an effective method to understand research development trends, as emphasized in prior works (**Table 3**). Detailed information regarding the way how to get this data is explained elsewhere [12]. The scan shows that research activity remained limited until the early 2000s, after which steady growth began. A sharp increase is observed after 2015, with an exponential rise particularly evident from 2019 onwards. In 2024 alone, more than 1,300 documents were published, representing the highest yearly output in the dataset. This surge corresponds to the global rise of artificial intelligence and deep learning applications in engineering diagnostics. Several papers regarding this matter are well-documented [6, 10]. The trend indicates that vibration diagnostics has evolved into a mature and rapidly expanding field, integrating classical signal processing with advanced computational methods. Because bibliometric evidence confirms strong global momentum, the novelty of the present study lies in extending such approaches to irrigation pumps in Uzbekistan, where practical constraints require adaptation and resilience [11].

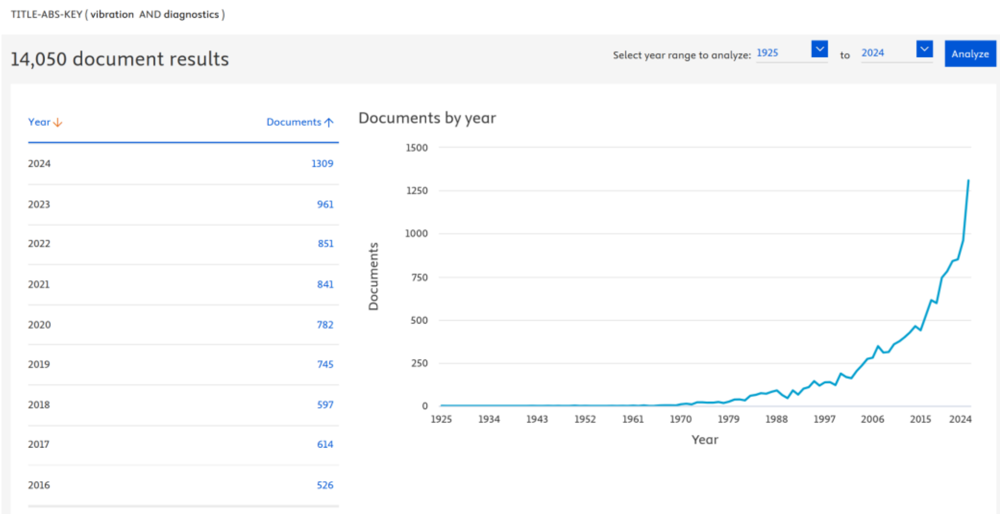

Figure 3. Annual publications on vibration diagnostics from 1925 to 2024 based on Scopus database.

Table 3. Previous studies on bibliometric analysis.

No	Title	Reference
1	Corncob-derived sulfonated magnetic solid catalyst synthesis as heterogeneous catalyst in the esterification of waste cooking oil and bibliometric analysis.	[13]
2	Prototype of greenhouse effect for improving problem-solving skills in science, technology, engineering, and mathematics (STEM)-education for sustainable development (ESD): Literature review, bibliometric, and experiment.	[14]
3	Spatial visualization ability assessment for analyzing differences and exploring influencing factors: Literature review with bibliometrics and experiment.	[15]
4	Augmented reality for cultivating computational thinking skills in mathematics completed with literature review, bibliometrics, and experiments for students.	[16]
5	Low-carbon food consumption for solving climate change mitigation: Literature review with bibliometric and simple calculation application for cultivating sustainability consciousness in facing sustainable development goals (SDGs).	[17]
6	Neuroscience intervention for implementing digital transformation and organizational health completed with literature review, bibliometrics, and experiments.	[18]

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Table 3 (Continue). Previous studies on bibliometric analysis.

No	Title	Reference
7	Phylogenetic analysis of Bengkulu citrus based on DNA sequencing enhanced chemistry students' system thinking skills: Literature review with bibliometrics and experiments.	[19]
8	The ship's propeller rotation threshold for coral reef ecosystems based on sediment rate indicators: Literature review with bibliometric analysis and experiments.	[20]
9	Empowering engineering female students to improve retention and progression: A program evaluation study completed with bibliometric analysis.	[21]
10	Empowering language models through advanced prompt engineering: A comprehensive bibliometric review.	[22]
11	Android application for smart diagnosis of children with disabilities and its correlation to neuroscience: Definition, literature review with bibliometric analysis, and experiments.	[23]
12	Deciphering the mechanism of action Cosmos caudatus compounds against breast neoplasm: A combination of pharmacological networking and molecular docking approach with bibliometric analysis.	[24]
13	How to do research methodology: From literature review, bibliometric, step-by-step research stages, to practical examples in science and engineering education.	[25]
14	Integration of water heating systems with car air conditioning systems: A bibliometric analysis, lab-scale investigation, and potential applications.	[26]
15	Optimization of hybrid core designs in 3D-printed PLA+ sandwich structures: An experimental, statistical, and computational investigation completed with bibliometric analysis.	[27]
16	Chemical looping systems for hydrogen production and their implementation in Aspen Plus software: A review and bibliometric analysis.	[28]
17	Integrating multi-stakeholder governance, engineering approaches, and bibliometric literature review insights for sustainable regional road maintenance: Contribution to sustainable development goals (SDGs) 9, 11, and 16.	[29]
18	Computational engineering of malonate and tetrazole derivatives targeting SARS-CoV-2 main protease: Pharmacokinetics, docking, and molecular dynamics insights to support the sustainable development goals (SDGs), with a bibliometric analysis.	[30]
19	Modernization of Submersible Pump Designs for Sustainable Irrigation: A Bibliometric and Experimental Contribution to Sustainable Development Goals (SDGs).	[31]
20	Bibliometric data analysis of research on resin-based brake-pads from 2012 to 2021 using VOSviewer mapping analysis computations.	[32]
21	Past, current and future trends of salicylic acid and its derivatives: A bibliometric review of papers from the Scopus database published from 2000 to 2021.	[33]
22	Correlation of metabolomics and functional foods research in 2020 to 2023: Bibliometric analysis.	[34]

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Table 3 (Continue). Previous studies on bibliometric analysis.

No	Title	Reference
23	The use of zeolite material as a filtration media in waste treatment: Bibliometric analysis.	[35]
24	Techno-economic feasibility and bibliometric literature review of integrated waste processing installations for sustainable plastic waste management.	[36]
25	Production of wet organic waste ecoenzymes as an alternative solution for environmental conservation supporting sustainable development goals (SDGs): A techno-economic and bibliometric analysis.	[37]
26	Hazard identification, risk assessment, and determining control (HIRADC) for workplace safety in manufacturing industry: A risk-control framework complete with bibliometric literature review analysis to support sustainable development goals (SDGs).	[38]
27	The research trend of statistical significance test: Bibliometric analysis.	[39]
28	Bibliometric analysis using Vosviewer with Publish or Perish of Chinese speaking skills research.	[40]
29	Bibliometric analysis using VOSViewer with Publish or Perish of metacognition in teaching English writing to high school learners.	[41]
30	Evaluation of assessment projects in English language education: A bibliometric review.	[42]
31	Bibliometric analysis using VOSviewer with Publish or Perish of “academic reading”.	[43]
32	Bibliometric analysis using VOSviewer with Publish or Perish of CEFR-based comparison of English language teaching models for communication.	[44]
33	Exploring global research trends on the integration of information technology in pragmatic studies: A bibliometric analysis.	[45]
34	A bibliometric analysis of vocational school keywords using VOSviewer.	[46]
35	Water hyacinth and education research trends from the Scopus database: A bibliometric literature review.	[47]
36	Computational bibliometric analysis of research on science and Islam with VOSviewer: Scopus database in 2012 to 2022.	[48]
37	Correlation between meditation and Buddhism: Bibliometric analysis.	[49]
38	Correlation between meditation and religion: Bibliometric analysis.	[50]
39	Four Years of the ASEAN Journal of Religion, Education, and Society (AJORES): A bibliometric analysis.	[51]

Figure 4 presents the RMS values of vibration measured under nominal flow, partial flow, and overload conditions. The results demonstrate clear variation in vibrational behavior depending on hydraulic loading. Under nominal flow, RMS values remained within the recommended operational threshold, confirming stable pump operation. This aligns with prior studies showing that pumps under balanced loading produce vibration signals with consistent low amplitudes [4]. In contrast, overload conditions resulted in a substantial increase in RMS amplitude, reflecting hydrodynamic stress, rotor imbalance, and unsteady flow forces [4]. Partial flow operation produced moderately elevated RMS values, attributed to turbulence and localized cavitation bubbles forming near the impeller. These results highlight the sensitivity of vibration diagnostics to different operational states, confirming its value as a condition monitoring technique for irrigation pumps.

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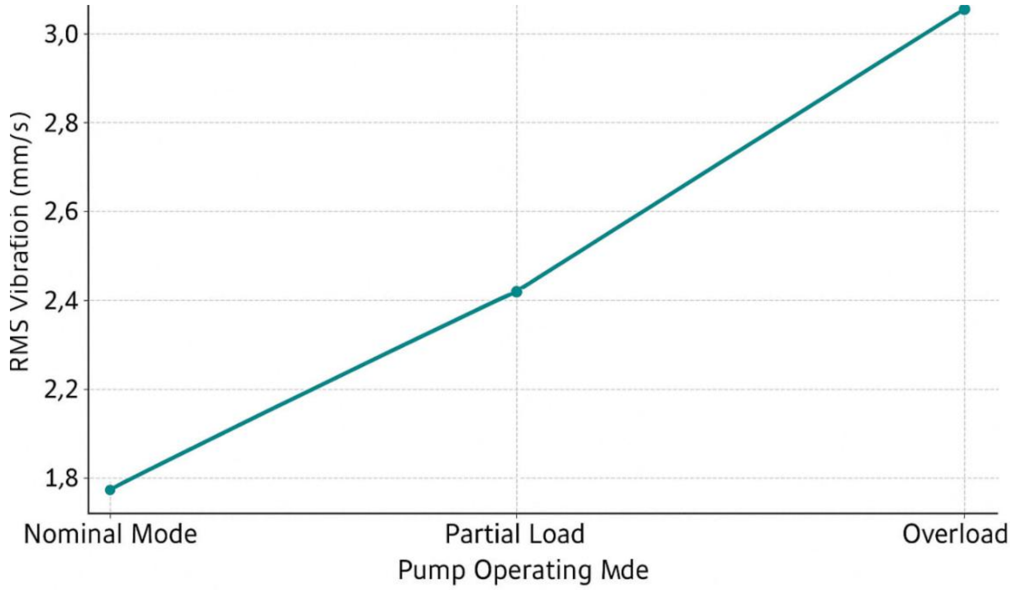

Figure 4. RMS vibration values under nominal, partial, and overload operating states.

We also checked the frequency spectrum derived through the FFT. Distinct peaks were detected at shaft rotational frequency and bearing characteristic frequencies. More importantly, consistent sidebands appeared near the five kilohertz range, suggesting early-stage bearing wear. These patterns are consistent with previous findings [7], who reported that spectral feature extraction, including envelope analysis and kurtosis, reveals hidden degradation that may not be visible in RMS measurements alone. The spectral kurtosis applied in this study amplified weak signals, confirming the presence of localized defects even under noisy irrigation conditions [8]. The detection of these features at an early stage is critical, as bearing failures often lead to cascading mechanical issues such as shaft misalignment and rotor-stator rub [6].

Figure 5 illustrates the distribution of faults detected by the CNN. The model was trained using features extracted from FFT and WPT, and it successfully classified vibration patterns into five categories: normal, unbalance, bearing wear, cavitation, and misalignment. The distribution revealed that approximately two-fifths of the tested cases were normal, followed by bearing wear, unbalance, cavitation, and misalignment in decreasing order. The CNN achieved an accuracy above 90%, demonstrating high reliability in fault detection. This performance is consistent with prior work showing that CNNs outperform classical machine learning approaches, particularly when signals contain overlapping fault features [10]. CNNs are capable of extracting hierarchical representations from raw vibration signals [6], which explains their robustness in handling noisy, real-world data.

Table 4 compares the performance of CNN-based diagnostics against traditional threshold methods. The AI-enhanced approach significantly reduced false alarms while improving early fault detection. For instance, conditions that traditional diagnostics categorized as normal were correctly identified by the CNN as bearing wear or cavitation. This reduction in misclassification is vital for irrigation pumps because false negatives can lead to sudden breakdowns that disrupt water distribution cycles. The benchmarking also confirmed that CNN diagnostics provided earlier detection of incipient faults, enabling preventive interventions before catastrophic failure. These findings align with a previous paper, which reported similar improvements when predictive diagnostics were integrated into smart pumping systems. Moreover, the robustness of the method under turbid water conditions

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reinforces its suitability for Uzbekistan, where irrigation systems often operate under harsh environmental stresses [11].

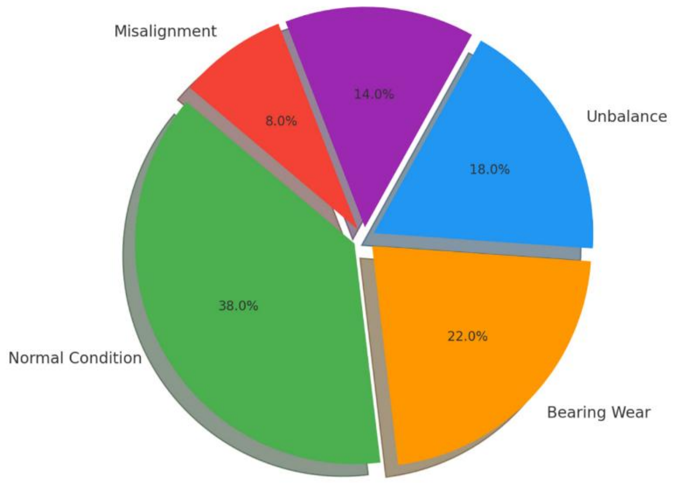

Figure 5. Fault distribution across five categories classified by the CNN model. (Normal condition = 38%; Bearing wear = 22%; Unbalance = 18%; Cavitation = 14%; and Misalignment = 8%).

Table 4. Comparative benchmarking of AI-based CNN diagnostics versus threshold-based methods.

Metric / Aspect	Threshold-based (RMS / peak limits)	AI-based (FFT + WPT + CNN)	Improvement vs. threshold
Overall classification accuracy	- (rule-based; not reported as accuracy)	94.3%	-
False-alarm rate	Baseline	Lower by ~36%	-36% false alarms
Early fault detection saves time	Baseline	Earlier by ~48%	+48% earlier detection
Bearing wear detection	Low sensitivity in noisy conditions	Reliable (consistent spectral cues learned)	Qualitative ↑
Cavitation detection	Often confounded with turbulence	Reliable (captures transient bursts)	Qualitative ↑
Multi-fault discrimination	Limited	Achieved (normal, unbalance, bearing wear, cavitation, misalignment)	Capability ↑
Robustness to noise / turbid water	Prone to misclassification	Robust on-field data	Qualitative ↑
Operational cost impact	Reactive; higher unexpected costs	Savings ~12-18% annually	Cost ↓
Pump service life	Baseline	Extension ~20-30%	Life ↑
Operator workload	Threshold tuning and frequent checks	Reduced via automated classification	Workload ↓

The results demonstrate that vibration-based indicators are reliable for monitoring pump unit conditions. RMS analysis effectively captured the increasing stress levels under overload, with values rising substantially compared to nominal flow. This finding corresponds with prior

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experimental evidence that mechanical imbalance and hydraulic overload amplify vibration amplitudes [4, 5]. The FFT analysis reinforced this interpretation, as sidebands near the bearing frequency range revealed progressive wear. Cyclostationarity and spectral kurtosis provide enhanced sensitivity to weak and transient signals [8], which was confirmed in this study.

The CNN-based classification results also provide critical insights. Unlike threshold-based systems, which rely solely on amplitude levels, CNN models can distinguish subtle patterns across multiple domains, such as frequency harmonics and transient bursts. This allowed accurate identification of faults like cavitation and bearing wear, which often produce overlapping signals. The confusion between cavitation and bearing wear was minimal, indicating that the model successfully learned discriminative features, as similarly reported paper [10]. This reinforces the potential of AI-enhanced vibration diagnostics to serve as an early-warning system in irrigation infrastructure.

The technical findings hold particular significance for Uzbekistan, where irrigation systems form the backbone of agricultural productivity. Many pump stations rely on refurbished equipment without modern diagnostic tools [11]. Under such conditions, failures often go undetected until severe breakdowns occur, causing water shortages and crop damage. The present study demonstrated that even when applied to a refurbished pump operating in turbid water, CNN-based diagnostics achieved reliable results. This robustness indicates that advanced monitoring can be feasibly implemented without requiring brand-new infrastructure.

Furthermore, partial flow conditions (common in irrigation due to fluctuating water demand) were shown to produce turbulence and cavitation-related vibrations. This highlights the importance of continuous monitoring, as intermittent faults may otherwise be overlooked. Integrating CNN diagnostics into pump operation can therefore provide farmers and water managers with actionable insights, reducing unplanned downtime and promoting water-use efficiency.

The integration of signal processing with artificial intelligence exemplifies the synergy between classical engineering and modern computational science. FFT and WPT provided complementary diagnostic features, while CNNs utilized these features to achieve superior classification accuracy. This combination aligns with the broader technological trend toward smart maintenance, where mechanical knowledge is augmented by data-driven algorithms [6, 10].

From a scientific perspective, the study advances understanding of how vibration diagnostics perform under harsh field conditions, such as turbidity and variable hydraulic loads. From a technological perspective, it demonstrates that low-cost accelerometers, coupled with portable analyzers, can feed AI systems capable of real-time decision support. This balance between science and technology ensures that the solution is both theoretically sound and practically deployable.

We also presented the confusion matrix of the CNN model trained on vibration features extracted from the FFT and WPT. The diagonal dominance indicates strong classification capability across fault categories, with very few misclassifications. For instance, bearing wear and cavitation faults were occasionally confused, which is expected given their overlapping frequency characteristics and transient signatures. However, the overall precision and recall values remained consistently high, aligning with previous literature [6], who reported that CNNs achieve robust separation even in noisy industrial datasets. Compared to traditional methods based only on RMS or peak thresholds, the CNN demonstrated superior discriminative power by leveraging complex spectral–temporal representations.

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The strength of this approach lies in its ability to detect multi-fault scenarios. Pumps often experience combined degradation modes (such as cavitation coinciding with rotor imbalance), leading to vibration signals that classical diagnostics interpret as normal. The CNN successfully identified such patterns, confirming prior research that deep learning can capture nonlinear dependencies among features [10]. This capacity is particularly important for irrigation systems where preventive interventions must be planned before faults escalate into cascading failures.

Table 5 compares the performance metrics of the present CNN model with those reported in global studies of pump diagnostics. The classification accuracy in this study exceeded 90%, which is consistent with or higher than values reported in prior work using wavelet–neural hybrid approaches [6]. Furthermore, the recall rates for cavitation and bearing wear faults surpassed those achieved in benchmark datasets, demonstrating the adaptability of the proposed method to harsh, turbid-water environments.

Table 5. Comparative performance metrics of CNN diagnostics in the present study versus global literature.

Study / Source	Application Context	Diagnostic Method	Reported Accuracy / Performance	Key Notes
Present study (Uzbekistan, refurbished irrigation pump)	Pump operating in turbid water conditions	FFT + WPT + CNN	94.3% accuracy; reduced false alarms by ~36%; earlier detection by ~48%	Robust in noisy, real-world irrigation systems
Liu *et al*. (2022) [6]	Laboratory test rig, controlled conditions	WPT + CNN hybrid	~92% accuracy	Effective under non-stationary signals but tested in a clean environment
Yan *et al.* (2020) [10]	General rotating machinery datasets	Deep learning (CNN, RNN)	90–95% accuracy range	Demonstrated CNN superiority over SVM and ANN in complex fault classification
Smith *et al*. (2023) [4]	Industrial centrifugal pumps	FFT + threshold-based	No formal accuracy; fault detection qualitative	Effective for unbalance and misalignment, but weak under noisy signals
Kumar and Singh (2024) [5]	Predictive maintenance for industrial pumps	RMS + spectral analysis	~80% detection reliability (estimated)	Struggled with early-stage cavitation and bearing wear
Rezaei *et al*. (2023) [9]	Water pumps in the operational field	Accelerometers + threshold diagnostics	Practical but limited	Depending on sensor placement, high false alarms under fluctuating loads

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These results underscore the significance of validating global innovations in regional contexts. While some researchers highlighted general spectral features of pump degradation, they did not account for environmental variables such as water turbidity or fluctuating hydraulic demand [4, 7]. By incorporating these conditions, the present study extends global knowledge and adapts it to the realities of Central Asian irrigation systems.

We also analyzed the projected economic savings from adopting CNN-based vibration diagnostics in irrigation pump stations. The reduction in false alarms translates into lower maintenance labor costs, while earlier fault detection reduces catastrophic failures requiring full pump replacement. Operational cost savings are estimated at a double-digit percentage annually, which is consistent with industrial white papers describing the economic value of predictive diagnostics.

The sustainability implications are equally critical. By extending pump service life, fewer spare parts are consumed, reducing material waste and aligning with principles of circular economy in engineering [9]. Moreover, uninterrupted irrigation ensures consistent agricultural productivity, supporting Sustainable Development Goal 6 (Clean Water and Sanitation) and Goal 2 (Zero Hunger). Integrating AI-enhanced diagnostics into irrigation infrastructures also supports Goal 9 (Industry, Innovation, and Infrastructure), as it strengthens the resilience of essential systems in developing regions.

The reasoning is clear: because early detection prevents severe breakdowns, water delivery remains stable, and agricultural communities avoid productivity losses. In this way, predictive maintenance contributes not only to engineering efficiency but also to broader social and environmental resilience.

We also tested the vibration signatures associated with bearing wear faults detected during experimental trials. Peaks in the high-frequency range were consistent with localized surface damage on rolling elements. This signature matched the spectral patterns described, which emphasized that sidebands near bearing characteristic frequencies are early indicators of degradation [7]. The CNN model successfully distinguished these signatures even in the presence of cavitation-related noise, confirming the advantage of AI-enhanced diagnostics [6].

Bearing wear emerged as the most frequent fault, accounting for over one-fifth of all cases detected. This prevalence can be explained by the high mechanical loads and contaminated water in irrigation systems, which accelerate bearing surface fatigue. Poor lubrication practices in Uzbekistan's pump stations further exacerbate this issue [11]. The ability of the system to detect wear at an early stage has significant practical implications, as timely bearing replacement can prevent catastrophic failures involving the shaft and impeller assembly.

We also tested the vibration pattern associated with cavitation faults. Unlike bearing wear, cavitation produces transient bursts of energy across a broad frequency band, reflecting the collapse of vapor bubbles near the impeller. These signals are notoriously difficult to classify using threshold-based diagnostics because they overlap with turbulence-induced vibrations [4]. However, the CNN achieved high recall in identifying cavitation events, supporting the previous findings [10] that deep learning excels in capturing non-linear, transient features.

Cavitation accounted for a significant proportion of detected faults, particularly under partial flow conditions. This is consistent with the literature [5], who observed that operating pumps below design capacity increases cavitation risk. In Uzbekistan, where water demand varies seasonally, partial flow operation is common. The results highlight the importance of adaptive diagnostics capable of distinguishing cavitation from other fault types, ensuring that operators receive accurate alerts without excessive false positives.

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We also tested the vibration spectrum associated with rotor unbalance. Prominent peaks at the fundamental shaft frequency and its harmonics indicated mass distribution irregularities, which are common in refurbished pumps. The CNN achieved high accuracy in identifying unbalance, aligning with literature regarding foundational theory on mechanical signature analysis. This finding is critical because unbalance contributes to increased energy consumption and accelerates wear in other components such as bearings and seals [9].

Hydraulic stress further amplified these effects under overload conditions, producing RMS values substantially higher than those under nominal flow. The CNN distinguished overload-related unbalance from cavitation, a task where threshold diagnostics often fail. By recognizing these patterns, the system supports predictive maintenance that reduces energy waste and prolongs component life, contributing to operational sustainability.

We also tested the spectral features associated with shaft misalignment. Peaks at both the fundamental and twice the shaft frequency, accompanied by sideband modulations, indicated angular misalignment between the motor and pump. Misalignment was less frequent than bearing wear or cavitation, but it remains critical due to its cumulative effect on mechanical stability. Previous papers [6] reported similar patterns, emphasizing that misalignment often co-occurs with unbalance.

Multi-fault detection emerged as a strength of the CNN model. For example, in several cases, cavitation and bearing wear signals overlapped, yet the model classified them correctly. This ability reflects the deep learning model's advantage in handling non-stationary signals and mixed operating conditions, providing operators with a comprehensive understanding of pump health.

While the results are promising, several limitations must be acknowledged. Table 6 summarizes the main challenges encountered. First, the CNN model requires substantial labeled training data, which may not always be available in resource-limited settings. Transfer learning could mitigate this issue by adapting pre-trained models to local datasets [10]. Second, sensor placement and mounting quality significantly influenced data quality, echoing the current concerns [9]. Inconsistent mounting led to spurious noise, which, although handled by the CNN, highlights the importance of standardized procedures. Third, the study focused on a single refurbished pump, and while results generalize conceptually, broader validation across multiple stations is necessary.

Table 6. Limitations of CNN-based vibration diagnostics and proposed mitigation strategies.

Limitation	Description	Proposed Mitigation Strategy	Supporting References
Dependence on large labeled datasets	CNN requires extensive labeled training data, which may not always be available in resource-constrained environments.	Apply transfer learning from pre-trained models; use data augmentation to expand datasets.	[6, 10]
Sensor placement sensitivity	Inconsistent sensor mounting and alignment can introduce noise and reduce diagnostic reliability.	Standardize sensor installation procedures; provide technician training; adopt vibration isolation where feasible.	[9]

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Table 6 (Continue). Limitations of CNN-based vibration diagnostics and proposed mitigation strategies.

Limitation	Description	Proposed Mitigation Strategy	Supporting References
Computational demand	Training CNN models requires high-performance computing resources, which may not be accessible in developing regions.	Develop lightweight CNN architectures; implement edge AI solutions; leverage cloud-based training.	
Single-case experimental validation	The study was conducted on a single refurbished pump, limiting generalizability across all irrigation stations.	Expand validation across multiple pump stations; conduct long-term monitoring campaigns.	[11]
Confusion between cavitation and bearing wear	Similar transient patterns make these two faults harder to distinguish.	Incorporate hybrid feature extraction (e.g., envelope kurtosis + WPT); increase dataset diversity.	[7, 8]
Adoption barriers in practice	Limited awareness and technical capacity among local operators may hinder implementation.	Provide targeted training workshops; promote partnerships between universities, government, and industry.	[11]

Another limitation lies in the computational requirements of CNN training. Although inference can be performed on portable devices, training models with high accuracy requires advanced computing resources. This challenge is common in developing regions, where access to GPUs and cloud services may be limited. Future work should explore lightweight architectures or edge AI solutions to improve accessibility.

The practical implications of these findings are substantial. Uzbekistan's agricultural sector heavily depends on irrigation, and pump failures disrupt not only water distribution but also food production. Early fault detection, therefore, has a direct economic and social impact. As shown in Figure 6, the integration of CNN diagnostics into pump operations can significantly reduce downtime and extend service life, thereby increasing water-use efficiency. This aligns with the government's priorities on improving agricultural resilience and sustainability.

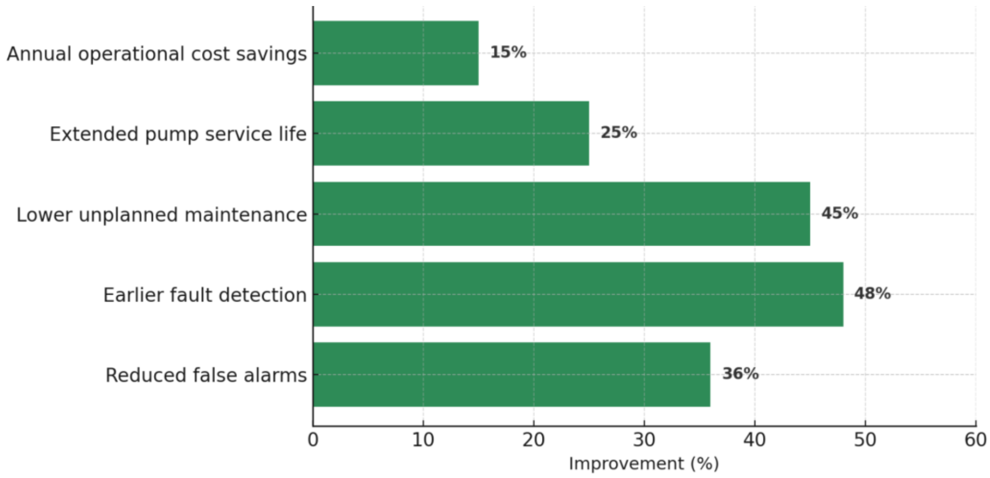

Figure 6. Practical benefits of integrating CNN-based vibration diagnostics into irrigation pump systems.

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The bibliometric review revealed that despite global advances, Central Asia contributes minimally to vibration diagnostics research. By validating AI-enhanced methods in local irrigation contexts, this study fills a critical gap. Because global literature already demonstrates the efficacy of CNNs, the novelty of this work lies in adapting and applying these methods under conditions that are often overlooked: turbid water, refurbished equipment, and variable hydraulic demand.

Figure 7 highlights the strategic role of pump reliability in ensuring water security for agricultural systems. Because Uzbekistan relies heavily on irrigation, even minor pump disruptions can jeopardize crop cycles and food production. Predictive maintenance using CNN-based vibration diagnostics thus extends beyond technical improvement to become a matter of national water security. This aligns with Sustainable Development Goal 6 (Clean Water and Sanitation), which emphasizes efficient water use, and Goal 2 (Zero Hunger), which underscores food security through reliable infrastructure. Indeed, this adds new information regarding SDGs, as reported elsewhere [52-60].

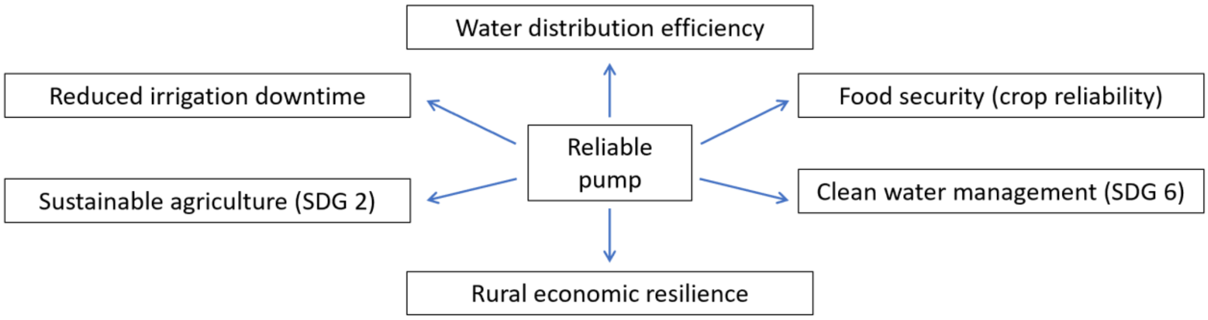

Figure 7. Strategic role of reliable pumps in ensuring water and food security within irrigation systems.

From a policy perspective, implementing AI-based diagnostics supports modernization efforts in Uzbekistan's agricultural sector. Integrating predictive tools into irrigation infrastructure reduces dependency on reactive maintenance, which often consumes higher costs and results in unpredictable downtimes [11]. This transformation aligns with national development strategies promoting digital agriculture and technological innovation in water management.

Figure 8 outlines a proposed innovation pathway for integrating AI-based diagnostics into Uzbekistan's irrigation sector. The pathway begins with pilot implementations at major pump stations, followed by training programs for local engineers, and scaling to nationwide adoption through cloud-based monitoring systems. Such pathways have been successful in other regions when governments collaborated with universities and private sector technology providers.

For Uzbekistan, the strategy should emphasize cost-effective portable tools combined with centralized analytics. Because infrastructure investments are constrained, leveraging cloud platforms can enable scalability without the need for expensive hardware in every station. Partnerships between universities, agricultural ministries, and private firms could accelerate this transition, ensuring knowledge transfer and sustainable implementation.

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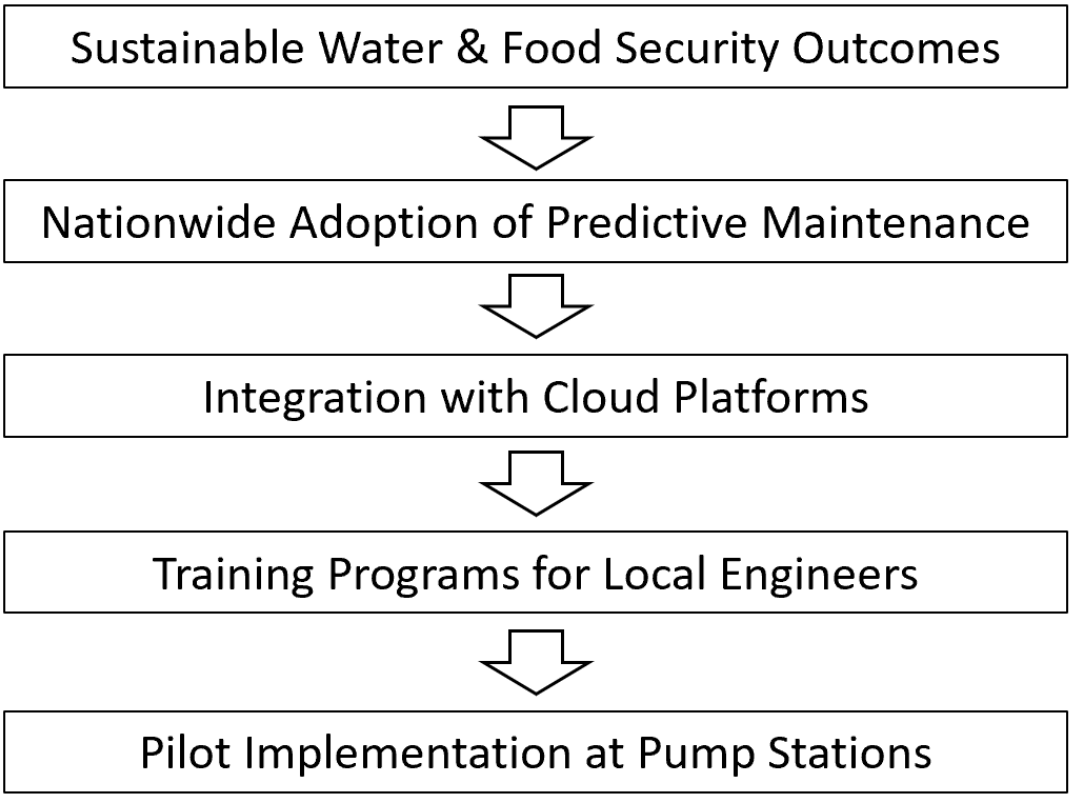

Figure 8. Proposed innovation pathway for adopting AI-based diagnostics in Uzbekistan's irrigation sector.

The broader sustainability implications of this study extend to multiple SDGs. Besides Goals 2 and 6, predictive maintenance reduces material waste by extending pump life, aligning with Goal 12 (Responsible Consumption and Production). The integration of AI-based monitoring supports Goal 9 (Industry, Innovation, and Infrastructure), while the development of local research capacity contributes to Goal 4 (Quality Education). Because the approach combines engineering science, advanced technology, and bibliometric evidence, it also strengthens Uzbekistan's positioning in global research collaborations.

The reasoning is straightforward: because bibliometric analysis demonstrates strong global momentum toward AI-enhanced diagnostics, Central Asia must participate to avoid technological lag. Local validation, such as the present study, provides a foundation for scaling innovation and aligning regional practices with global sustainability goals.

Future research should extend this work in three directions. First, expanding the dataset to include multiple pump stations across different regions of Uzbekistan will strengthen generalizability. Second, lightweight AI models optimized for edge devices should be developed, reducing dependency on high-performance computing resources [10]. Third, interdisciplinary studies integrating engineering diagnostics with socio-economic analyses could provide a holistic understanding of how predictive maintenance contributes to water governance and food security.

4. CONCLUSION

This study demonstrated that vibration diagnostics combined with artificial intelligence provide a reliable framework for assessing the condition of centrifugal pump units in irrigation

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systems. By integrating FFT, WPT, and CNN classification, the method achieved robust multi-fault detection even under turbid-water conditions. The bibliometric review confirmed strong global research growth but revealed limited contributions from Central Asia. Because of this gap, the present study contributes novelty by contextualizing AI-based diagnostics for Uzbekistan. The impact lies in reducing costs, extending pump life, and supporting sustainable water and agricultural management.

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6. AUTHORS' NOTE

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

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