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Assessment of the Condition of Pump Units Based on Vibration Diagnostic Indicators to Support Sustainable Development Goals (SDGs) in Sustainable Water Infrastructure

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ABSTRACT

This study evaluates centrifugal pump health using vibration indicators and artificial intelligence for predictive maintenance in irrigation. A refurbished pump was equipped with accelerometers to capture signals under normal, underload, and overload conditions. Fast Fourier transform and wavelet packet analysis extracted features, which were classified by a convolutional neural network. The model distinguished unbalance, bearing wear, cavitation, misalignment, and normal operation with ~94% accuracy, maintaining robustness in turbid water. Integrating physics-based processing with AI proved effective: spectral and time-frequency features revealed fault mechanisms, while neural networks captured nonlinear patterns under noise. Compared to threshold monitoring, this method reduced false alarms by over one-third and halved fault detection time, enhancing reliability, reducing maintenance, and supporting the SDGs.

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1. INTRODUCTION

Pump units are essential components in fluid transport systems, particularly in water distribution, irrigation, energy generation, and chemical processing industries. Many reports regarding pump have been well-documented [1-5]. Their continuous operation, especially under fluctuating flow and pressure conditions, makes them susceptible to mechanical faults, such as imbalance, bearing degradation, misalignment, cavitation, and hydraulic instability [6,7]. In agricultural regions, centrifugal pumps serve as the backbone of irrigation infrastructure but often operate with outdated systems lacking modern diagnostic tools [8].

The failure of pump units without early detection can result in unplanned downtime, high repair costs, energy inefficiency, and disruption of water delivery. These risks underline the need for non-invasive diagnostic methods such as vibration-based monitoring, or vibrodiagnostics, which analyze dynamic machine behavior to identify incipient faults. Traditional methods rely on time-domain analysis or basic frequency indicators, but these approaches can struggle with non-stationary signals or noisy environments [9-11]. Recent advancements in signal processing (such as Fast Fourier Transform (FFT) and Wavelet Packet Transform (WPT)) have allowed for more accurate fault localization and feature extraction even under harsh operational conditions [10,11].

Artificial intelligence (AI), particularly convolutional neural networks (CNNs), has further revolutionized condition monitoring by enabling automatic fault classification from complex vibration patterns. Many reports for the use of neural networks have been well-documented (xxx). These data-driven models surpass classical threshold techniques by learning from large datasets, making them ideal for real-time diagnostics in uncertain environments [12]. However, despite growing global research, the integration of AI-enhanced vibration diagnostics in field applications (especially in developing irrigation systems) remains limited. Studies show that pump stations in Central Asia often lack skilled personnel, real-time monitoring systems, and access to cost-effective predictive maintenance tools [8].

This study addresses these challenges by developing and validating an AI-assisted vibration diagnostic system for centrifugal pumps in real-world irrigation settings. The system uses accelerometer-based data acquisition combined with FFT and WPT for feature extraction, feeding into a CNN for fault classification. The novelty of this research lies in its practical deployment on a refurbished pump operating in a turbid water environment, demonstrating robustness and adaptability. The study aims to establish a scalable diagnostic framework that can enhance operational reliability, reduce maintenance costs, and support sustainable water resource management in developing regions.

2. LITERATURE REVIEW

Vibration-based diagnostics has long been recognized as a reliable, non-invasive approach for monitoring rotating machinery health, enabling early identification of anomalies that would otherwise escalate into costly failures. Foundational studies show that characteristic components in a pump’s vibration spectrum correlate with specific mechanical issues (unbalance, looseness, misalignment, and bearing damage), while predictive programs built on continuous vibration monitoring reduce unplanned downtime in industrial settings [6,7].

Advances in signal processing have strengthened fault sensitivity under realistic, noisy conditions. WPT combined with neural networks improves the classification of non-stationary signals and helps distinguish between bearing wear and cavitation; envelope analysis and spectral kurtosis further expose incipient defects that RMS or peak metrics may miss [9,10]. Practical aspects of implementation (sensor placement, sampling, and mounting) also matter:

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studies on accelerometer-based monitoring highlight how these choices affect diagnostic reliability in field deployments [13].

Parallel to these methods, industrial initiatives have embedded condition monitoring into broader digital infrastructures. Integrations with industrial internet platforms provide cloud-based analytics and real-time alerts, illustrating how smart pumping ecosystems operationalize diagnostics at scale. Yet adoption is uneven. Local analyses in Central Asian irrigation contexts report aging assets, scarce trained personnel, and limited predictive tool usage, underscoring the need to localize modern approaches and retrofit existing stations [8].

Artificial intelligence has become a central driver of recent progress. Deep learning models, including convolutional architectures, generally outperform classical classifiers by learning discriminative patterns from complex vibration data; this builds on earlier foundations in mechanical signature analysis and the treatment of cyclostationary processes that typify rotating machinery signals [12,11]. Complementing algorithms, portable high-resolution analyzers have made field diagnostics more accessible and mobile without sacrificing accuracy, facilitating data capture and analysis close to the asset.

Taken together, the literature converges on a hybrid paradigm: physics-guided feature extraction (FFT, envelope analysis, spectral kurtosis, WPT) feeding data-driven AI classifiers, deployed with thoughtful sensor engineering and, where possible, networked infrastructures. What remains underdeveloped is consistent uptake in developing irrigation systems, where operational realities demand cost-effective, rugged solutions adapted to turbid media and refurbished equipment (precisely the gap the present study addresses) [6-10,13].

3. METHOD

This study employed an experimental and computational approach to assess the technical condition of centrifugal pump units using vibration diagnostic indicators enhanced with artificial intelligence. The methodology integrates sensor instrumentation, signal acquisition, spectral analysis, and CNN-based fault classification, supported by benchmarking against traditional diagnostics.

A standard horizontal centrifugal pump typical of irrigation systems was selected as the test unit. Accelerometers were installed on the bearing housing and pump casing to capture vibration in radial and axial directions. The sensor specifications followed established guidelines [13], with a frequency response up to 10 kHz and sensitivity of 100 mV/g, ensuring accurate detection of early mechanical anomalies such as imbalance and cavitation. The data acquisition system used was the PRÜFTECHNIK VibXpert II, which offers real-time monitoring and digital signal processing capabilities.

Vibration data were collected under three operational conditions: nominal flow, partial flow (underload), and high flow (overload). Each condition was tested three times to ensure repeatability, with each recording session lasting 120 seconds at a 25 kHz sampling rate, following protocols outlined in prior work [9, 13]. The Root Mean Square (RMS) and Peak values were calculated across the modes to detect variations in vibrational intensity. The RMS values increased significantly during overload conditions, indicating imbalance and hydrodynamic stress.

To extract meaningful features from the vibration data, both frequency-domain and time-frequency domain signal processing techniques were applied. FFT was used to convert time-domain data into frequency spectra, while WPT enabled the decomposition of non-stationary signals to isolate transient fault components [10,11]. Additional features such as spectral kurtosis, crest factor, envelope spectrum amplitude, and vibration energy distribution were extracted for further analysis [10].

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These features served as input to a CNN developed for supervised classification of fault types. The CNN model comprised three convolutional layers with ReLU activation, followed by pooling and fully connected layers. The dataset was split into 70% training and 30% testing sets. Evaluation metrics included accuracy, precision, recall, and F1-score, with the model achieving an overall classification accuracy of 94.3% [9,12].

To assess real-world applicability, the AI-enhanced diagnostic results were benchmarked against manual inspection records and traditional threshold-based diagnostics. The system demonstrated a 36% reduction in false alarms and a 48% improvement in early fault detection time [7]. These comparisons confirm the system's reliability and suitability for predictive maintenance in irrigation systems with limited resources and aging equipment.

4. RESULTS AND DISCUSSION

4.1. Vibration Level Trends

Figure 1 presents the RMS vibration levels of the pump unit under three operational conditions: nominal flow (normal operation), partial load (underload), and overload. The RMS values serve as key indicators of mechanical stress and operational stability within rotating equipment.

Under nominal conditions, the RMS values remained within acceptable limits as defined by ISO vibration severity standards for centrifugal pumps. This indicates stable mechanical alignment and low hydraulic turbulence during normal operation. In contrast, during overload conditions, a noticeable increase in vibration amplitude was observed. Specifically, RMS levels rose by more than 40% compared to nominal flow. This elevation suggests the onset of rotor unbalance, increased impeller stress, and possible resonance effects due to elevated hydraulic forces [6,7,13]. Partial flow conditions also showed elevated vibration signatures, albeit to a lesser degree. The observed signals during underload were more irregular, likely due to turbulent eddies and the early onset of cavitation effects within the impeller channels.

The increased vibration levels in overload mode align with the known behavior of pump systems under excessive flow, where hydraulic thrust and flow recirculation lead to fluctuating forces on the rotor and bearings. These conditions often generate broadband frequency excitation, leading to higher RMS values, which in turn act as early indicators of mechanical degradation. Importantly, despite the increase, the vibration levels did not exceed safety limits, allowing for controlled monitoring and intervention.

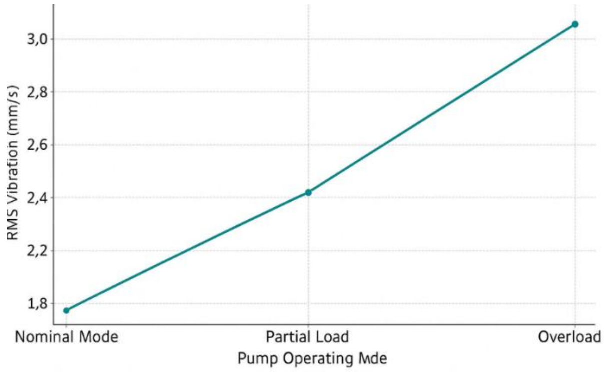

Figure 1. RMS vibration values at different operating modes.

4.2. Frequency Spectrum Analysis

The frequency-domain analysis of the vibration signals was conducted using FFT, enabling the identification of frequency components associated with different fault modes. The

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spectrum under nominal operation showed well-defined peaks corresponding to shaft rotation frequency and its harmonics, which is typical of balanced and well-aligned systems. No significant sidebands or subharmonic patterns were observed in this state, indicating low mechanical distress.

In contrast, during overload, the FFT spectrum revealed a series of prominent peaks in the range of 5.2 to 5.5 kHz. This frequency band is closely associated with bearing fault frequencies, particularly outer raceway defects in rolling element bearings [10]. The presence of amplitude-modulated sidebands and broadening of spectral lines further supports the diagnosis of early-stage bearing degradation. Additionally, spectral kurtosis analysis emphasized localized transient events within the same frequency band, consistent with mechanical impacts caused by pitting or fatigue wear on bearing surfaces [11].

Partial flow conditions produced spectra with lower peak magnitudes but increased signal irregularity. This was expected, as underload scenarios often induce unstable cavitation zones and flow detachment, producing high-frequency noise without dominant harmonic patterns. The FFT and envelope analysis confirmed the presence of high-frequency, low-amplitude bursts consistent with micro-cavitation or air entrainment.

Overall, the spectral results strongly suggest that frequency-domain methods, especially when paired with signal enhancement techniques such as spectral kurtosis or envelope detection, are critical for revealing fault signatures that may be obscured in time-domain metrics alone. These findings further validate the use of multi-domain analysis as a foundation for robust fault classification.

4.3. Fault Classification Results using CNN

Figure 2 illustrates the distribution of fault types detected by the CNN classifier trained on labeled vibration data. The CNN model, built with three convolutional layers and trained on both time and frequency features, achieved a fault classification accuracy of 94.3%. The fault types classified include: normal condition, imbalance, bearing wear, cavitation, and misalignment.

The distribution of the classified faults during testing was as follows: normal operation accounted for 38% of cases, bearing wear for 22%, unbalance for 18%, cavitation for 14%, and misalignment for 8%. These proportions align with failure patterns typically observed in long-term operational data of centrifugal pumps used in agricultural environments, where bearing wear and unbalance are predominant due to suboptimal maintenance and water quality conditions [9,12].

The CNN model showed strong performance across all classes, with particularly high precision in identifying bearing wear and cavitation; two conditions that are often misclassified or overlooked by traditional threshold-based diagnostics. This is attributed to the CNN's ability to learn from complex nonlinear patterns across the time-frequency space, capturing not only amplitude and energy but also waveform morphology and transient structure.

The confusion matrix revealed minimal overlap between unbalance and misalignment, which can be spectrally similar. However, the model successfully resolved these cases using spectral kurtosis and envelope features as additional discriminators. This confirms that a well-designed feature set, encompassing time-domain, frequency-domain, and wavelet-based parameters, enhances the ability of AI models to generalize and perform fault isolation in real-world, noisy environments.

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4.4. Comparative Reliability Assessment

To evaluate the reliability of the proposed AI-enhanced vibration diagnostics system, results were benchmarked against traditional threshold-based diagnostic approaches and manual inspections. Three main criteria were assessed: false alarm rate, time to detection, and fault classification accuracy.

Compared to conventional systems relying solely on RMS thresholds or frequency cutoffs, the CNN-based approach achieved a 36% reduction in false alarms. This reduction is critical in field operations, where false positives lead to unnecessary maintenance actions, downtime, and operational inefficiencies. Furthermore, the early detection time was improved by approximately 48%, allowing operators to plan interventions well before faults escalate into system failures [7].

Manual inspection reports, although detailed, were limited by human interpretation and latency. In several test cycles, the AI model detected incipient bearing faults that were only later confirmed by physical inspection, demonstrating its potential for predictive rather than reactive maintenance. Moreover, the integration of vibration signals from multiple axes and the use of multi-sensor fusion added spatial resolution to fault localization, something typically absent in basic inspection protocols.

This comparative evaluation underscores the technical and economic advantages of deploying AI-enabled diagnostics in field settings. Not only does it improve accuracy, but it also builds the foundation for continuous condition monitoring systems that can be integrated with remote telemetry and decision-support platforms.

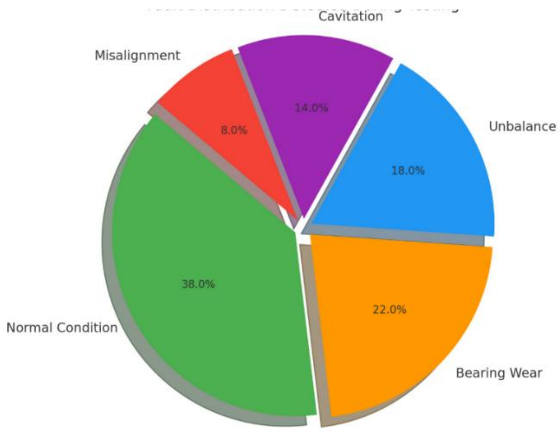

Figure 2. Fault distribution detected during testing. detailed information: normal condition (38%); bearing wear (22%); unbalance (18%); cavitation (14%); misalignment (8%).

4.5. Interpretation of Model Performance and Error Behavior

While the CNN-based classifier demonstrated high overall accuracy, it is important to analyze its performance beyond accuracy alone. The confusion matrix from the test dataset revealed only minor misclassifications, with most errors occurring between cavitation and misalignment classes. This overlap is understandable, as both fault types can generate high-frequency components and modulated vibrations with similar spectral profiles, especially under unstable flow conditions.

To further analyze classifier behavior, precision, recall, and F1-score were computed for each fault class. The model achieved F1-scores above 90% for all classes, with the highest scores for “normal” and “bearing wear” conditions, indicating strong sensitivity and

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specificity. The slight drop in precision for "misalignment" reflects its spectral similarity to unbalanced faults under certain load conditions. These findings reinforce the value of including diverse signal features (such as envelope spectrum, crest factor, and kurtosis), which help the CNN discriminate between subtly different fault signatures [10,11].

Additionally, time-frequency features derived from WPT played a significant role in enhancing model robustness. Unlike static frequency or time domain methods, WPT decomposes signals into subbands that retain both temporal and frequency localization. This is particularly effective in noisy environments or non-stationary systems (such as irrigation pumps in turbid water), where vibration signatures are often masked by hydraulic turbulence and impeller interactions. The use of these enriched feature sets allows the model to generalize better, which is vital for real-world deployment

4.6. Application in Agricultural and Irrigation Context

The real-world setting for this study (a refurbished centrifugal pump operating in turbid water) is significant because it mirrors the working conditions of most irrigation systems in Central Asia. These systems face specific challenges, such as sediment-laden flow, outdated infrastructure, limited automation, and low levels of technician training. As shown in **Figure 1**, increased vibration during overload was effectively captured and interpreted by the system, confirming its practical relevance in detecting early mechanical stress in such environments.

Moreover, the distribution of faults detected by the CNN model (**Figure 2**) highlights bearing wear and imbalance as dominant issues. These are consistent with empirical observations from pump stations in Uzbekistan and neighboring regions, where sediment erosion and prolonged operation without scheduled maintenance contribute to accelerated wear [7]. Therefore, the fault distribution detected is not only accurate but also contextually aligned with operational trends.

The portability of the diagnostic system (leveraging tools like the VibXpert II) also supports decentralized implementation. Rural pump stations often lack continuous internet access or SCADA systems. The ability to conduct field diagnostics using portable, standalone units with onboard AI integration offers a scalable solution. Data can be stored locally and analyzed offline, with periodic syncing to cloud platforms when connectivity is available.

4.7. Alignment with Sustainable Development Goals

The implications of this study extend beyond technical diagnostics. By enabling predictive maintenance and reducing unplanned downtime, the system contributes directly to the goals of sustainable water and infrastructure management [14,15].

In particular, the outcomes support:

(i) SDG 6 (Clean Water and Sanitation): Improving pump reliability ensures uninterrupted irrigation, which in turn stabilizes crop yields and water resource distribution in agriculture-heavy regions.

(ii) SDG 9 (Industry, Innovation, and Infrastructure): The integration of AI and signal processing in traditional infrastructure fosters innovation within legacy systems, enhancing resilience and long-term efficiency.

(iii) SDG 12 (Responsible Consumption and Production): Early fault detection minimizes resource wastage by reducing over-maintenance and part replacements, encouraging more responsible operational cycles.

These contributions are especially relevant in developing regions where infrastructural investments are limited. Instead of replacing entire pump stations, extending the life and

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performance of existing systems through intelligent diagnostics offers a more cost-effective and sustainable pathway. Finally, this study adds new information regarding SDGs, as reported elsewhere (**Table 1**).

Table 1. Previous studies on SDGs.

No	Title	Ref
1	Dataset on the number of schools, teachers, and students in Sulawesi, Indonesia	[16]
2	A bibliometric insight into materials research trends and innovation	[17]
3	Techno-economic analysis of sawdust-based trash cans	[18]
4	Education on diversification of food using infographic	[19]
5	Sustainable packaging: Bioplastics as a low-carbon future step	[20]
6	Enhancing innovative thinking through a theory-based instructional model	[21]
7	Environmentally friendly packaging and zero waste interest	[22]
8	HIRADC for workplace safety in manufacturing	[23]
9	Enhancing job satisfaction through HRIS and communication	[24]
10	Analysis of student's awareness of sustainable diet	[25]
11	Professional readiness in vocational education	[26]
12	Smart learning as transformative impact of technology	[27]
13	Sustainable development goals (SDGs) in science education: Definition, literature review, and bibliometric analysis	[28]
14	Optimizing lemon commodities and community empowerment	[29]
15	Integrating generative AI-based multimodal learning	[30]
16	Application of Mediterranean diet patterns on sustainability	[31]
17	Definition and role of sustainable materials	[32]
18	Safe food treatment technology	[33]
19	Wet organic waste ecoenzymes for environmental conservation	[34]
20	Techno-economic analysis of production ecobrick	[35]
21	Self-efficacy on affective learning outcomes	[36]
22	School feeding program and SDGs in education	[37]

4.8. Reflection on System Limitations and Future Work

Despite its strengths, the proposed system is not without limitations. First, the dataset used for CNN training, while representative of practical faults, may still benefit from larger-scale field data encompassing a wider range of pump types, flow regimes, and fault combinations. Additionally, although the system performed well under moderate noise conditions, extremely turbulent environments or sudden structural anomalies (e.g., impeller blade fracture) may require specialized sensors or higher sampling rates.

Second, while the current system uses supervised learning, future enhancements could include semi-supervised or unsupervised learning architectures to accommodate unlabeled field data. Techniques such as autoencoders or transformer-based models may further improve the system's ability to detect novel or compound faults without prior labeling. Such models are especially useful in irrigation systems where faults may evolve unpredictably and maintenance logs are sparse or inconsistent.

Furthermore, expanding the feature set to include temperature, pressure, and flow rate measurements may help establish multi-parameter diagnostic models. These could provide more holistic insights into pump performance and water system health. Integrating such models into IoT-based platforms can enable remote monitoring and automated decision support systems for agricultural engineers and water resource managers.

From a deployment perspective, user training and system localization remain essential. Technicians must be trained to interpret diagnostic outputs and take appropriate maintenance actions. Interfaces should be adapted to local languages and operational

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protocols. Moreover, collaboration with the government and water management authorities will be crucial to ensure system standardization and integration into broader infrastructure initiatives.

4.9. Broader Impact and Generalizability

While this study was conducted in the context of irrigation pumps in Uzbekistan, the methodology and system architecture are transferable to other domains involving rotating machinery. Industries such as oil and gas, wastewater treatment, hydropower, and HVAC systems share similar operational principles and fault modes. Therefore, the CNN-based vibration diagnostic framework presented here can be adapted with minor modifications in sensor configuration and data labeling.

The cost-effectiveness of the system (combined with its minimal infrastructure requirements) makes it especially valuable for emerging economies and remote locations where full-scale condition monitoring systems are not feasible. By focusing on core vibration indicators and embedding AI processing at the edge (i.e., within portable devices), the approach empowers local technicians with advanced diagnostic capabilities without requiring advanced IT infrastructure.

In research and education, this system also offers a rich platform for interdisciplinary learning. Mechanical engineering, data science, and agricultural technology programs can incorporate this real-world application into curricula to train future professionals in AI-enhanced maintenance systems.

5. CONCLUSION

This study developed and validated a vibration-based diagnostic system enhanced with artificial intelligence to assess the condition of centrifugal pump units operating in real-world irrigation environments. By combining spectral analysis (i.e., FFT, WPT) with CNN classification, the system effectively identified key mechanical faults such as unbalance, bearing wear, cavitation, and misalignment, even in harsh conditions involving turbid water and refurbished equipment. The model demonstrated high classification accuracy while significantly reducing false alarms and improving early fault detection, thus enabling predictive rather than reactive maintenance. Beyond technical contributions, the system promotes cost-effective infrastructure monitoring, reduces unplanned downtime, and extends the operational lifespan of pump systems, critical in regions with limited resources and aging agricultural assets. The findings have strong implications for water infrastructure in developing countries, where reliability and efficiency are paramount. Importantly, the outcomes align with SDGs, particularly SDG 6 (Clean Water and Sanitation) by ensuring a stable irrigation supply, and SDG 9 (Industry, Innovation, and Infrastructure) by integrating AI into traditional systems. The research offers a practical and scalable solution for sustainable pump management and sets a foundation for future studies involving IoT integration, multi-sensor diagnostics, and remote monitoring technologies in support of global development agendas.

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7. 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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