

Review

Intelligent Reliability of Ferrofluid Seals: A Review

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Abstract

Ferrofluid seals provide non-contact operation, low friction, and strong sealing performance in high-speed rotating equipment and liquid-sealing systems. However, high speed, liquid contact, thermal loading, vibration, and eccentricity can cause ferrofluid loss, performance degradation, leakage, and premature failure. Here, intelligent reliability denotes a reliability-centered framework that integrates condition monitoring, physically interpretable health assessment, fault diagnosis, uncertainty-aware prognosis, condition-based maintenance, and feedback-driven active control. This structured review synthesizes centrifugal, thermal, liquid-medium, eccentricity-related, and material-degradation mechanisms and evaluates pressure, leakage, temperature, torque, vibration, and acoustic-emission signals. It also assesses health indicators, diagnostic methods, remaining useful life (RUL) prediction, maintenance decisions, and health-management strategies. Its principal contribution is a framework linking degradation physics with observable evidence, health assessment, diagnosis, prognosis, and maintenance and design feedback. The framework also distinguishes direct ferrofluid-seal evidence from transferable methods and supports sensor selection, indicator design, validation planning, and intervention development. Key limitations include scarce public degradation datasets, inconsistent evaluation protocols, weak physical consistency of health indicators, and limited closed-loop implementation. Future work should prioritize public run-to-failure data, physics-informed multisource assessment, uncertainty-aware RUL prediction, and experimentally validated condition-based interventions and active-control strategies.

Keywords: ferrofluid seal; intelligent reliability; fault diagnosis; remaining useful life prediction; health management



Academic Editor: Norman M. Wereley

Received: 4 July 2026

Revised: 1 August 2026

Accepted: 5 August 2026

Published: 6 August 2026

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1. Introduction

A ferrofluid seal uses an external magnetic field to form a magnetization-pressure barrier in the sealing gap. This non-contact sealing mode provides low friction, rapid response, and the potential for near-zero leakage. It is therefore valuable for high-speed rotating machinery, vacuum devices, liquid-medium isolation, and sealing in special environments. Compared with conventional contact seals, ferrofluid seals can reduce friction and wear while maintaining strong sealing performance, and they have attracted sustained research interest across a broad range of scientific and engineering applications. Existing studies show that appropriate structural design and magnetic-circuit configuration can improve pressure resistance and operational stability. For example, high-speed pressure-resistance tests reported stable operation for 3 h at 0.1 MPa and a linear speed of 47 m/s, with the

temperature eventually stabilizing at 39 °C. Studies on distributed structures for large-diameter shafts also indicate that optimized pole-tooth and magnetic-isolation designs can reduce magnetic leakage and improve pressure resistance [1–3].

Ferrofluids and their sealing applications emerged from the mid-twentieth-century development of ferrohydrodynamics. Foundational analyses and experiments established how magnetic body forces, magnetization pressure, gravity, and interfacial tension jointly determine the equilibrium and stability of magnetic-fluid interfaces [4,5], while Rosensweig's monograph consolidated the governing thermomagnetic and hydrodynamic framework [6]. These principles were translated into rotary-shaft hardware in early patent and engineering work: the modular magnetic-fluid seal patent described multistage liquid rings retained in focused magnetic gaps [7], and early dynamic-seal studies developed design relations for radial clearance, differential pressure, rotary speed, and torque [8]. By the late 1970s and 1980s, magnetofluid seals had been demonstrated in high-vacuum and cryogenic rotating equipment [9], while analytical relationships between seal geometry and performance characteristics were established and compared with experimental data [10]. Subsequent high-speed experiments examined the effects of rotational loading on sealing capability and failure [11]. Classical interface-stability studies established the physical balance among magnetic stress, gravity, and interfacial tension, providing a theoretical basis for subsequent analyses of magnetic-fluid interfaces under liquid-medium sealing conditions [4,5]. On this foundation, the current research frontier has expanded from static pressure capacity to condition monitoring, reliability assessment, fault diagnosis, remaining useful life prediction, and closed-loop health management.

Between 2009 and 2019, independent research teams extended the engineering evidence base through direct ferrofluid-seal studies in miniature pneumatic and hydraulic actuators, rotary blood pumps, and underwater robotic vehicles [12–14]. Additional work addressed static seal capacity and large-clearance operation [15,16], thermal and operating-condition effects [17], water-environment durability [18,19], stage-wise pressure behavior [20], free-surface and particle-diffusion stability modeling [21], and special-environment pump applications [22].

As equipment speeds, medium complexity, and long-term service requirements increase, the reliability of ferrofluid seals in engineering applications has become increasingly important. In liquid media, especially water or coolant environments, two-fluid friction and interfacial instability are more pronounced and can readily induce leakage and shorten service life. Studies have shown that the service life of ferrofluid seals in water varies distinctly with rotational speed: seals fail more quickly in high-speed regimes but last much longer at lower speeds. Experiments on underwater leakage mechanisms and durability further indicate that liquid-medium operating conditions are a major bottleneck for engineering applications of ferrofluid seals [23–25]. Assembly eccentricity and structural asymmetry can also make the magnetic induction, magnetic force, and magnetization pressure in the gap non-uniform, which accelerates leakage or failure at local weak regions. Visualization studies of liquid-seal failure further show that interfacial instability and barrier damage are key causes of reliability degradation [26,27]. Under high-speed operation, centrifugal force and viscous shear drive ferrofluid migration and alter the interface morphology, weakening the magnetization-pressure barrier. Heat accumulation can also change viscosity and magnetic properties, promote carrier-fluid volatilization or loss, and gradually degrade sealing performance [28,29].

Beyond structural optimization and failure-mechanism analysis, ferrofluid-seal research has increasingly moved toward condition monitoring and intelligent state recognition. Multisource signals, including acoustic emission, pressure, temperature, torque, and vibration, have been used for condition identification, fault diagnosis, and degradation

monitoring in ferrofluid seals and related sealing systems. Acoustic-emission-based state recognition and flow-state discrimination have shown particular promise. In parallel, studies on degradation identification and service-life prediction using acoustic emission, time-series analysis, and intelligent algorithms in other sealing systems provide useful references for ferrofluid-seal reliability research [30–34].

Existing reviews address complementary material, sealing, application, and design questions. Material-oriented reviews describe ferrofluid synthesis, stabilization, and magnetic, rheological, and thermal properties [35]. Seal-oriented reviews summarize sealing principles, configurations, performance, and applications [36], while broader visualization studies map the development of ferrofluid research across multiple engineering fields [37]. Most recently, Zhen et al. [38] reviewed the intelligent design of ferrofluid seals specifically for ultra-high-vacuum applications. That review organizes the literature around UHV service requirements, vacuum-specific failure constraints, and intelligent design or performance-prediction methods, including multiphysics simulation, parametric and multi-objective optimization, topology optimization, data-driven identification, and emerging physics-informed learning. It gives particular attention to low-vapor-pressure fluids, outgassing, cleanliness, bake-out compatibility, thermal stability, liquid-ring retention, and reliable UHV operation.

The present review addresses a different, although partly overlapping, question. Rather than concentrating on UHV-specific seal design, it examines how degradation under high-speed, thermal, liquid-medium, eccentricity/disturbance, and intrinsic material conditions can be converted into observable evidence for condition monitoring, health-indicator construction, fault diagnosis, uncertainty-aware prognosis, remaining useful life prediction, condition-based maintenance, and feedback-driven active control. Its distinctive contribution is therefore a cross-application reliability-and-validation framework rather than a UHV-specific intelligent-design review or a proposal for a new seal structure. It distinguishes direct, foundational, transferable, and proposed evidence; quantitatively compares the experimental context and diagnostic validation of representative primary studies; defines the calibration and uncertainty requirements of candidate health indicators; and proposes run-to-failure, held-out-condition, external-rig, and detect-decide-act-verify validation pathways. The two reviews share necessary background in ferrofluid-seal physics and selected design methods, but differ in application boundary, organizing question, evidence treatment, life-cycle tasks, and engineering outputs. Detailed UHV-specific questions such as gas-load control, bake-out qualification, and low-outgassing intelligent design are not reviewed exhaustively here; readers are referred to Zhen et al. [38]. Conversely, the present review treats UHV only as one possible service context and focuses on reliability evidence, monitoring, diagnosis, prognosis, maintenance, and validation across broader operating conditions.

1.1. Review Scope, Search Strategy, and Evidence Classification

This article is a structured critical review rather than a meta-analysis or a formal systematic review. It focuses on the failure mechanisms, observable signals, health indicators, fault diagnosis, remaining useful life (RUL) prediction, condition-based maintenance, and health-management strategies of ferrofluid seals. Direct theoretical, numerical, and experimental studies of ferrofluid seals constitute the primary evidence base. Where direct evidence is limited, methods from related seals, valves, pumps, hydraulic systems, and rotating machinery are considered only when their transferable status and limitations are explicitly stated. To improve the transparency and reproducibility of the review, a supplementary search and reference audit was conducted on 28 July 2026 using Crossref Metadata Search and the local Zotero full-text library. The principal search terms included

“ferrofluid seal”, “magnetic fluid seal”, “ferrofluidic seal”, and “magnetofluid seal”, combined with terms related to reliability, failure, degradation, leakage, monitoring, diagnosis, prognosis, remaining useful life, maintenance, and health management. Topic-specific combinations additionally covered high-speed operation, thermal behavior, liquid-medium sealing, eccentricity, vibration, acoustic emission, pressure, torque, and service life. No lower publication-year limit was imposed because foundational ferrohydrodynamic theory and early seal-development studies predate modern database coverage. Backward and forward citation tracking was also used to identify seminal books, patents, early experiments, and relevant subsequent studies. The supplementary search returned 125 records, including 120 Crossref records and five records from the local full-text library. After duplicate Crossref returns and repeated local copies were removed, 62 unique records underwent title-and-metadata or available-abstract screening. Three review articles [35–37] were retained specifically to support the comparison of previous review scopes. Two targeted update searches were subsequently conducted on 31 July 2026. The first identified the recently published ultra-high-vacuum-focused review [38], and the second identified a material-property study on magneto-dielectric anisotropy, which was included as foundational evidence [39]. The review ultimately included 118 sources identified from the previously verified topic-specific literature, the local full-text collection, the supplementary searches, and backward and forward citation tracking. The 125-to-62 screening counts therefore describe the supplementary audit rather than the complete historical evidence corpus of the review. Sources were retained when they provided at least one of the following: (1) direct evidence on ferrofluid-seal structure, sealing capacity, degradation, leakage, monitoring, diagnosis, prognosis, maintenance, or intervention; (2) foundational ferrohydrodynamic, magnetic-fluid, material-property, or seal-performance evidence required to establish the physical basis of the review; or (3) transferable methodological evidence from a related engineering system when the similarity of the sensing principle, degradation process, or reliability task could be justified. Peer-reviewed journal articles were prioritized. Selected books, patents, conference papers, theses, and preprints were retained only when they supplied foundational or otherwise unavailable information. Duplicate records, superseded versions, studies without a clear relationship to ferrofluid-seal reliability, bibliographically unverifiable records, and studies unable to support a specific manuscript claim were excluded. Screening depth depended on the role of each source. Titles and bibliographic metadata were checked first, followed by available abstracts and full texts. For the quantitative studies discussed in Sections 3 and 4, the study object, ferrofluid or sealed medium, operating conditions, experimental duration, failure criterion, measured signals, dataset construction, validation split, reported metrics, and evidence limitations were additionally examined. Evidence status is distinguished at the level of the claim. Direct evidence refers to results obtained from a ferrofluid-seal object. Foundational evidence supports the underlying physical, material, or performance principles but does not independently validate an intelligent diagnostic, prognostic, maintenance, or control method. Transferable evidence refers to methods demonstrated on related engineering systems and is not treated as direct ferrofluid-seal validation. Proposed evidence denotes health indicators, sensor combinations, maintenance mappings, validation protocols, or implementation pathways synthesized in this review but not yet validated as complete ferrofluid-seal solutions. Because the search was conducted as a supplementary evidence audit rather than a prospectively registered systematic-review protocol, no claim of exhaustive database coverage is made.

1.2. Definition and Functional Boundaries of Intelligent Reliability

Intelligent reliability is not used here as a universally standardized discipline or as a synonym for artificial intelligence. In this review, it denotes a reliability-centered engineering paradigm that integrates condition-dependent sensing, physically interpretable health representation, diagnostic inference, uncertainty-aware prognosis, risk-informed condition-based maintenance decisions, and, where appropriate, feedback-driven active control to preserve the sealing function of a ferrofluid seal under variable operating conditions. The intelligence lies in converting monitored evidence into traceable assessments, decisions, and feedback, rather than merely applying a machine-learning algorithm.

Within this paradigm, condition monitoring acquires, synchronizes, preprocesses, and extracts features from pressure, leakage, temperature, torque, vibration, acoustic-emission, and operating-condition records and identifies departures from an established baseline. It provides current state information but does not, by itself, determine the fault cause, fault location, or remaining life. Fault diagnosis estimates the current abnormal state, fault type, location, or dominant degradation mechanism. Prognosis, including remaining useful life (RUL) prediction, estimates the future evolution of a health indicator and the time or probability of reaching a documented functional-failure threshold, together with the associated uncertainty. State-classification accuracy is not RUL performance, and early warning alone is not a quantitative RUL estimate without a time-evolution model, a failure threshold, and uncertainty treatment.

Condition-based maintenance (CBM) uses the assessed current condition, predicted risk, failure consequence, resource constraints, and safety requirements to decide whether and when to inspect, derate, replenish, repair, replace, or shut down the seal system. Active control is a distinct online execution layer that automatically modifies controllable variables, such as rotational speed, differential pressure, cooling intensity, ferrofluid replenishment rate, or start-up profile, according to feedback, a control rule, an actuator, and predefined safety constraints. Supervisory or human-authorized operating adjustments are treated as online interventions or condition-based maintenance execution rather than active control unless the final actuation is governed automatically by a feedback law. Condition-based maintenance may be performed manually and does not necessarily involve active control; active control should not be interpreted as fault diagnosis or prognosis. Manual replenishment, planned inspection, and component replacement are ordinarily CBM actions rather than continuous active control.

Accordingly, condition monitoring answers what is being observed and whether the monitored response has changed; fault diagnosis asks what is wrong now, where it is occurring, and what the likely cause is; prognosis estimates when functional failure may occur; condition-based maintenance determines what action should be taken and when; and active control determines how an approved operational action is implemented online. Figure 1 organizes these functions as a review-level evidence chain. Their possible engineering connection is discussed later as a proposed implementation pathway rather than evidence that a fully validated autonomous closed-loop system is already available for ferrofluid seals.

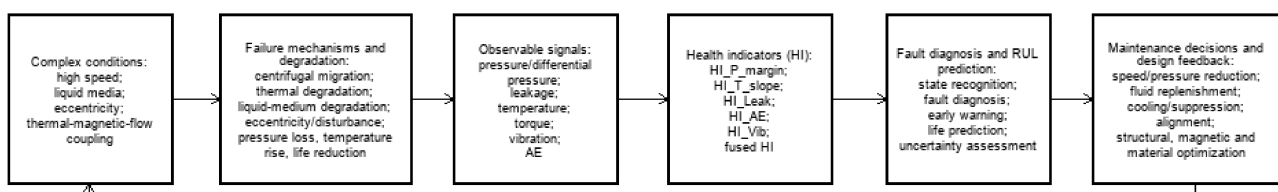


Figure 1. Review-level conceptual organization of the evidence chain for the intelligent reliability of ferrofluid seals.

Figure 1 outlines the organization of this review and the link from classical ferrohydrodynamic principles to intelligent reliability. Section 2 establishes the physical degradation reference framework; Section 3 considers observable signals and health-indicator construction; Section 4 evaluates diagnostic and prognostic methods; and Section 5 considers maintenance triggers, interventions, and feedback. Section 6 identifies the data, indicator, validation, and closed-loop implementation gaps that limit engineering deployment, and Section 7 summarizes the resulting reliability framework. The review critically integrates and evaluates these stages while preserving the distinction between direct ferrofluid-seal evidence and transferable methods.

The framework integrates evidence of different maturity levels: Sections 2 and 3 contain substantial direct mechanism, performance, and monitoring evidence; Section 4 combines limited direct diagnostic evidence with transferable diagnostic and prognostic methods; and Sections 5 and 6 include evidence-informed maintenance mappings and proposed implementation pathways requiring further ferrofluid-seal validation.

Figure 1 serves as a review-level conceptual map. It organizes the evidence synthesized in Sections 2–6 from complex operating conditions and degradation mechanisms to observable signals, health indicators, diagnosis/prognosis, and maintenance or design feedback. Its purpose is to clarify the logical structure of the review rather than to prescribe a specific engineering control architecture.

In this hierarchy, monitoring and health assessment provide the evidence layer, diagnosis and prognosis provide the inference layer, and condition-based maintenance and active control represent distinct decision and execution layers.

2. Failure Mechanisms and Performance Degradation of Ferrofluid Seals

A ferrofluid seal uses an external magnetic field to retain ferrofluid within the sealing gap. The field creates a magnetization-pressure difference across the liquid ring, thereby isolating the sealed medium. For a single-stage ferrofluid ring, the sustainable pressure difference is:

$$\Delta p = \mu_0 \int_{H_1}^{H_2} M(H) dH \quad (1)$$

Here, Δp is the pressure sustained across the ferrofluid ring, μ_0 is the vacuum permeability, and $M(H)$ is the magnetization at field strength H . H_1 and H_2 are the magnetic-field strengths on the two sides of the ring, respectively.

The magnetic-pressure relation in Equation (1) follows the ferrohydrostatic balance obtained by integrating the magnetization over the magnetic-field variation across the fluid interface. Its application assumes quasi-static equilibrium of the ferrofluid ring [4–6].

If the ferrofluid approaches magnetic saturation, Equation (1) can be simplified for engineering analysis as:

$$\Delta p \approx \mu_0 M_s \Delta H \quad (2)$$

Here, M_s is the saturation magnetization, and ΔH is the magnetic-field-strength difference across the ring. Equation (2) is an engineering saturation approximation, not a universal constitutive relation. It applies only when $M(H)$ remains approximately M_s over the relevant field range [6,10].

Equations (1) and (2) show that pressure capacity depends on ferrofluid magnetization and the magnetic-field difference across the sealing gap. A sufficiently large field gradient enables the liquid ring to maintain a stable magnetization-pressure barrier. Centrifugal loading, heat accumulation, eccentricity, and liquid-medium erosion can redistribute the ferrofluid or reduce magnetization and the field difference. These changes reduce the available pressure margin and may cause lower pressure capacity, increased leakage, or

seal failure. Equation (1) therefore links the physical source of sealing capacity to the degradation mechanisms examined below.

To review the failure evolution logic associated with operating-condition disturbances, Figure 2 summarizes the principal centrifugal, thermal, liquid-medium, and eccentricity/disturbance-driven degradation paths. Intrinsic ferrofluid and material degradation is discussed separately in Section 2.5 because it involves multicomponent chemical, colloidal, and compatibility changes that are not fully represented in the figure.

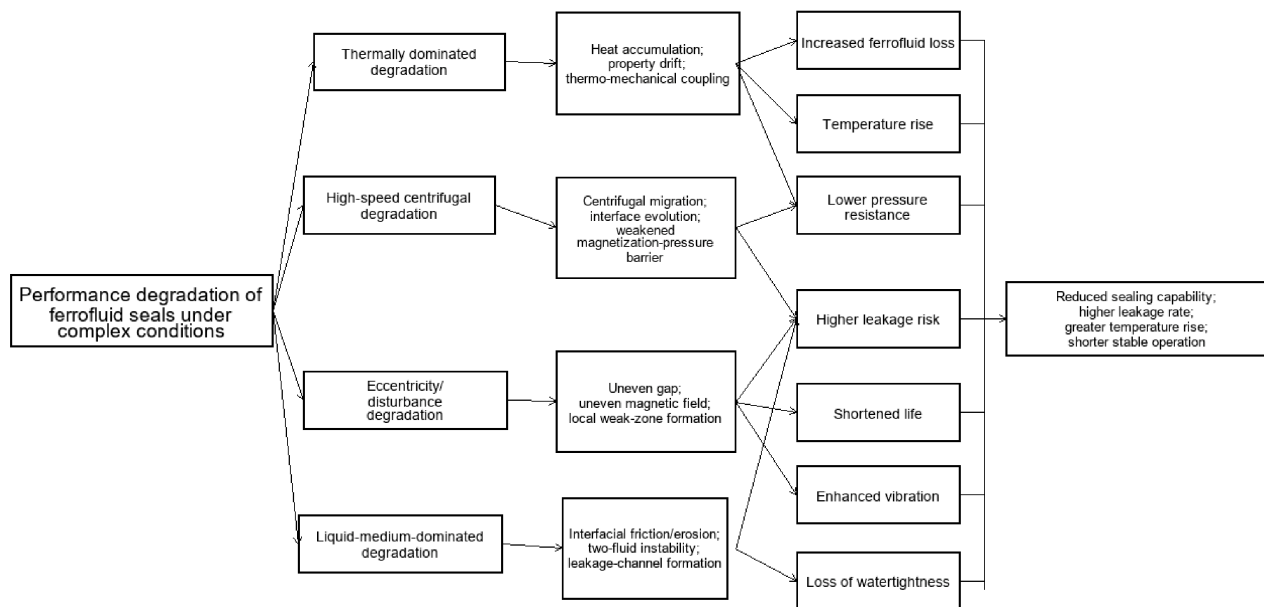


Figure 2. Main operating-condition-driven failure mechanisms and performance-degradation paths of ferrofluid seals.

Figure 2 summarizes four operating-condition-driven paths: high-speed centrifugal migration, thermally dominated degradation, liquid-medium instability, and eccentricity/external disturbances. Intrinsic ferrofluid and material degradation is a separate process that can couple with these paths through carrier, surfactant, particle, chemical, and compatibility changes. Together, these processes can contribute to reduced pressure resistance, increased leakage, temperature rise, or shortened service life.

2.1. Centrifugal Migration and Barrier Breakdown Under High-Speed Operation

At high rotational speeds, the ferrofluid is subjected to both magnetic confinement and centrifugal loading. Centrifugal force drives radial outward migration, redistributes the liquid ring, and weakens the local magnetization-pressure barrier. The resulting additional pressure difference can be approximated as:

$$\Delta p_c = \frac{1}{2} \rho \omega^2 (r_2^2 - r_1^2) \quad (3)$$

Here, Δp_c is the additional pressure difference generated by centrifugal action, ρ is the ferrofluid density, and ω is angular velocity. The terms r_1 and r_2 denote the inner and outer boundary radii of the ferrofluid ring, respectively.

The rotational term represents the radial hydrostatic-pressure contribution of a rotating liquid. Early rotary-seal research examined the competition between magnetic retention and rotational loading by considering differential pressure, rotational speed, frictional torque, and high-speed failure [8,11].

Equation (3) shows that the centrifugal pressure contribution increases with the square of angular velocity. Higher speeds drive outward ferrofluid migration and interface redistribution, changing the effective fluid volume within the sealing gap. If centrifugal loading approaches the pressure reserve of the magnetization barrier, the liquid ring may become unstable or fail locally. High-speed studies observed marked interface deformation and fluctuations that impaired pressure transmission and sealing performance [29,40]. Appropriate magnetic-circuit and structural designs can delay this failure. One device maintained 0.1 MPa for 3 h at 47 m/s, with its temperature stabilizing at 39 °C [1]. Pole-tooth geometry, magnetic isolation, and gap size also affect high-speed performance, and their optimal values vary with speed [2,29]. Visualization studies further indicate shorter service life as rotational speed, sealing pressure, and gap size increase [41]. Thus, centrifugal degradation is a major source of performance loss and a key target for structural optimization and condition monitoring. Independent analyses related static capacity and centering performance to magnetic saturation and geometry [15]. Large-clearance experiments demonstrated the effects of radial clearance, ferrofluid volume, and shaft rotation [16].

2.2. Thermally Dominated Degradation and Its Effects on Sealing Performance

Temperature rise both reflects energy dissipation and accelerates degradation in high-speed ferrofluid seals. Viscous dissipation, local friction, and other losses cause heat to accumulate during prolonged operation. Rising temperature can alter viscosity, saturation magnetization, particle stability, and interfacial properties, thereby reducing pressure margin and increasing ferrofluid loss [28,42]. Thermally dominated degradation therefore follows a coupled sequence: heat accumulation, property drift, declining sealing performance, and further acceleration of degradation.

Early high-speed cryostat applications demonstrated magnetic-fluid seals under high rotational velocity, low temperature, and high vacuum [9]. These results highlight the need to account for thermal and operating limits during seal design.

Existing research has analyzed thermal degradation at different levels. Inadequate heat dissipation and ferrofluid loss under high-speed operation are important contributors to ferrofluid-seal failure [42]. Meanwhile, experimental and numerical studies of thermal behavior in the sealing gap have shown that ferrofluid temperature continues to increase with rotational speed and exhibits clear thermal-equilibrium evolution under different heating conditions [28]. In addition, deformation of the shell structure under thermal-mechanical load also changes the sealing-gap distribution and further affects the magnetic field and flow state. Reliability optimization studies show that improving the cooling structure can significantly reduce the local maximum temperature and improve structural reliability under thermal-mechanical coupling conditions [43]. Independent bench measurements on magnetic-fluid seals for electric-motor shafts further quantified how shaft speed, pole/sleeve surface roughness, and ambient temperature affect friction torque and seal temperature [17].

Thermally dominated degradation is not limited to changes in the physical properties of the ferrofluid itself. It also involves heat-transfer coupling among the housing, shaft system, and medium, as well as the effect of thermal deformation on sealing-gap redistribution. For ferrofluid seals, thermal degradation should therefore be interpreted through heat sources, heat-transfer pathways, and thermal-parameter drift. Temperature rise, steady-state temperature difference, and heating rate can serve as important indicators of sealing-performance degradation and provide a basis for temperature monitoring, health-indicator construction, and thermal-management strategy design.

2.3. Interfacial Instability and Durability Decline in Liquid Media

Failure mechanisms in liquid media are more complex than those in gas or vacuum environments. Continuous relative motion couples the ferrofluid interface to the sealed liquid. Failure reflects interfacial instability, barrier damage, and local leakage-channel formation, rather than pressure difference alone [27]. Erosion, compression, and disturbance by the liquid medium destabilize the ring and promote ferrofluid migration, rupture, and loss [23,27]. Sealing performance consequently declines over time.

Magnetic-fluid interface stability reflects competition among magnetic stress, gravity, and interfacial tension. Classical theoretical and experimental studies established this balance [4,5].

Water provides a representative environment for assessing liquid-medium durability. Studies define service life as the number of rotations before watertightness is lost and report a nonlinear dependence on speed [23]. Durability decreases substantially at higher speeds. Further experiments identified two-fluid friction and interfacial instability as key failure causes [24]. Optimizing ferrofluid formulation, stage width, and fluid volume improved long-term stability, including tests exceeding 4.3 million rotations without failure [24]. These results show that liquid-medium performance depends on both seal structure and fluid-medium compatibility. Earlier tests assessed critical pressure, critical rotational velocity, and service life for single-stage water seals [18]. Separate blood-pump studies demonstrated shielded magnetic-fluid seals during continuous liquid flow and extended operation [13,19].

Mechanistic studies have also motivated strategies for improving liquid-condition durability. A replenishment system can continuously replace degraded ferrofluid during dynamic liquid contact and extend service life under pressurized conditions [25]. Because liquid-medium degradation evolves over long periods, static structural optimization alone is unlikely to eliminate it. Medium compatibility, ferrofluid replenishment or renewal, and operating-condition management should be considered together. Interfacial instability and durability loss remain major barriers to deployment and require attention in life prediction and maintenance planning.

2.4. Local Failure Induced by Eccentricity and External Disturbances

Shaft eccentricity, assembly error, and external vibration are difficult to eliminate in practical equipment. These disturbances alter the magnetic-field distribution and stress state within the sealing gap, creating conditions for local failure. In an ideal concentric seal, magnetic induction, magnetic force, and magnetization pressure are distributed relatively uniformly. Eccentricity introduces circumferential gap variation, makes the ferrofluid boundary asymmetric, and reduces local magnetization pressure. The resulting weak region can become the first leakage path.

Early patent and design studies established multistage magnetic-fluid seal configurations and general analytical relationships between seal geometry and performance characteristics [7,10].

Simulations show that increasing eccentricity amplifies non-uniformity in magnetic induction, magnetic force, and magnetization pressure, while progressively reducing sealing performance [26]. Vibration and large clearances further increase the risk of local instability. Large-gap structures designed for deformation, vibration, and radial oscillation showed more stable resistance under vibration [44]. This finding suggests that disturbance-tolerant structures can improve operational stability. Transferable studies indicate that vibration modulates leakage through changes in the gap and contact state [45]. Leakage peaks near resonance and decreases away from it. Vibration therefore acts not only as a

boundary disturbance but also as a dynamic excitation that can expand local weak regions into macroscopic leaks.

Eccentricity- and disturbance-dominated degradation does not usually eliminate sealing capacity immediately. It first produces non-uniform magnetic fields and gap distributions, followed by local failure and broader degradation. This pathway demands greater structural robustness, vibration monitoring, and alignment control. It also informs vibration-feature design and maintenance decision-making.

2.5. Intrinsic Ferrofluid and Material Degradation

Ferrofluid degradation should be distinguished from purely geometric or operating-condition-induced failure. A ferrofluid is a multicomponent colloidal system whose carrier liquid, surface-stabilization layer, magnetic particles, and interactions with adjacent materials can evolve during service. These changes may alter fluid volume, viscosity, magnetization, particle dispersion, interfacial tension, and wettability, thereby weakening the reproducibility of the magnetization-pressure barrier even when the nominal seal geometry remains unchanged. Material-focused ferrofluid literature summarizes the coupled roles of particles, surfactants, and carrier liquids in colloidal stability and rheology [35]. In the present review, these material-level mechanisms are separated from direct seal observations and are not treated as a universally diagnosed in-service state.

Carrier-fluid evaporation or volatilization is one possible route to a reduced fluid inventory, particularly when temperature, vapor pressure, exposed surface area, pressure environment, or gas flow favor loss of volatile components. It must not be used as a generic name for every reduction in ferrofluid volume. A high-speed ferrofluid-seal experiment directly visualized centrifugal accumulation and ejection from the gap [42]; this is a mechanical ejection mechanism, not an evaporation measurement. Liquid-medium extraction or erosion and leakage or migration out of the intended gap are also distinct routes. An observed reduction in ferrofluid volume does not by itself identify evaporation; centrifugal ejection, leakage, extraction by the sealed medium, and sampling or replenishment history must be excluded. Carrier loss may increase the effective particle fraction and viscosity initially, but continued loss can reduce liquid-ring coverage, create local weak regions, and decrease the available pressure margin.

Surfactants or surface coatings reduce particle attraction and help maintain a stable colloidal suspension. Elevated temperature, chemically incompatible media, oxidation-related surface changes, or long exposure may reduce the effectiveness of this stabilization layer; the resulting mechanism requires material-level verification rather than inference from an external temperature or leakage signal alone. Reduced surface coverage can promote particle association, sedimentation tendency, viscosity drift, altered wetting, and less reproducible interfacial behavior. Particle response should also be described carefully. Reversible field-induced chaining can occur during operation and should not automatically be classified as irreversible degradation. Persistent agglomeration after the field or operating disturbance is removed, irreversible aggregation, and sedimentation or phase separation are stronger material-degradation indications because they change the recovered dispersion or rheological state [35]. The engineering consequence is not determined by particle association alone. An increase in effective particle size may alter magnetic relaxation, local magnetization uniformity, gap flow, and the balance between viscous resistance and interfacial mobility. Particle-rich and particle-poor regions can then coexist, so bulk viscosity or a single magnetization measurement may not represent the local sealing ring. These pathways are physically plausible material mechanisms; the present seal literature does not establish a common in-service surfactant-degradation threshold or a universal particle-size limit for failure.

Material-level measurements also show that the electrical response of an oil-based ferrofluid can depend on field-dependent particle structuring. Hardoň et al. measured complex permittivity and dielectric loss in EMG-909 (10 nm Fe_3O_4 particles in light hydrocarbon oil) over 10 mHz–2 MHz at 15, 25, and 35 °C under magnetic flux densities up to 200 mT, and reported orientation-dependent magneto-dielectric anisotropy consistent with short field-aligned particle chains [39]. This supports dielectric spectroscopy as a possible complementary method for characterizing field-dependent microstructural changes in oil-based ferrofluids. However, the study did not investigate a ferrofluid seal, long-term material aging, or irreversible degradation. Field-induced chains may be reversible, and dielectric changes should not by themselves be interpreted as surfactant failure, irreversible aggregation, seal degradation, or a loss of pressure capacity.

Oxidation likewise requires a mechanism-specific interpretation. It may concern magnetic-particle or particle-surface chemistry, the carrier liquid, the surfactant, or corrosion products introduced from adjacent components. At the material level, oxidation can alter particle-surface interactions, dispersion stability, viscosity, acidity, or the magnetization curve; however, an observed decline in magnetization cannot be assigned to oxidation without excluding particle loss, dilution, temperature effects, formulation differences, and measurement uncertainty [35]. Contamination is broader than solid debris. Water ingress, sealed-medium intrusion, dust, metallic wear debris, corrosion products, incompatible lubricants or process fluids, and maintenance-introduced material can all modify composition or interfacial conditions. Water-environment studies directly show that ingress and interface evolution can be associated with leakage-channel development in a specific ferrofluid-seal arrangement [24], but they do not provide a universal chemical-contamination threshold.

Material compatibility therefore includes the carrier liquid with the sealed medium, the surfactant or particle coating with that medium, and the ferrofluid with metals, coatings, adhesives, elastomers, secondary seals, tubing, and replenishment-system materials. Temperature, pressure, polarity, corrosivity, and exposure time may change these interactions. Study [46] directly compared kerosene-, engine-oil-, and PAO-based magnetic fluids after 60 days of exposure to ethylene glycol and then reported a continuous 96 h zero-leakage test for the selected PAO-based formulation over -20 to 80 °C, at a maximum linear velocity of 0.1 m/s and a chamber pressure above 120 kPa. This is formulation- and condition-specific qualification, not proof that all PAO/ethylene-glycol systems are compatible. Study [47] directly compares pressure-resistance behavior for water- and kerosene-based fluids, two magnetic-particle mass fractions, and two capillary radii; it is a formulation/gap comparison rather than a long-duration aging or compatibility test. Study [48] provides a large-gap marine rotary-seal design and static pressure/leakage context, but not a chemical-corrosion exposure test. Application-specific compatibility evaluation should therefore consider controlled exposure, thermal or start–stop cycling, fluid inventory, rheology, magnetization, dispersion, interface behavior, secondary-material condition, and post-exposure pressure-capacity or leakage tests.

These mechanisms can reinforce one another without a fixed universal sequence. Carrier loss can increase effective particle fraction; surfactant deterioration can reduce colloidal stability; oxidation can alter particle-surface or fluid properties; and medium intrusion can introduce chemical or particulate contamination. Separate seal studies directly demonstrate thermophysical coupling without establishing long-term chemical aging: [49] relates shaft-speed-dependent viscous heating to temperature and viscosity in a high-speed ferrofluid sealer, whereas [50] reports formulation-specific thermal-conductivity, rheological, torque, temperature-rise, and pressure-capacity changes for a kerosene-based fluid containing 1 wt% carboxyl-functionalized long multi-walled carbon nanotubes. These results sup-

port thermal and formulation effects, not direct diagnosis of surfactant deterioration or oxidation. The resulting rheological, magnetic, and interfacial drift may produce ferrofluid redistribution or loss, pressure-margin decline, torque drift, leakage, and shortened life. Viscosity increase may raise torque and start-up resistance, whereas dilution may weaken liquid-ring retention; local particle-rich or particle-poor regions may reduce magnetic and rheological uniformity; and interfacial-tension or wettability drift may alter interface shape and leakage-channel formation. Pressure decline, torque increase, and leakage each remain non-unique outcomes. A pressure-margin decrease may result from fluid inventory loss, magnetization change, interface redistribution, or a concurrent geometry-related problem; similarly, torque drift can reflect viscosity change but can also include bearing, drive, or start-up effects. The most useful diagnosis is therefore a time-linked pattern that is consistent with a documented material exposure, not a threshold on one raw channel. For this reason, a material-degradation interpretation should combine condition-normalized online trends with service, replenishment, and exposure history rather than assign a cause from one signal. External online signals may indicate property drift, but material attribution generally requires exposure history and periodic or event-triggered fluid-property verification.

To summarize the five degradation pathways addressed in this section—centrifugal, thermal, liquid-medium, eccentricity/disturbance, and intrinsic ferrofluid/material degradation—Table 1 maps the associated degradation processes, observable responses, candidate health indicators, and possible actions.

Table 1. Mapping of ferrofluid-seal failure mechanisms to degradation processes, observable responses, health indicators, and possible actions.

Failure Mode	Dominant Operating Conditions	Intermediate Degradation Process	Leading Observable Responses	Candidate Health Indicators	Early-Warning Capability	Possible Operational or Maintenance Actions
High-speed centrifugal degradation	High speed; high differential pressure; continuous operation	Radial ferrofluid migration; interface deformation; local layer thinning; pressure-margin reduction	Differential-pressure decline or fluctuation; torque variation; temperature rise; later leakage	HI_P_margin; pressure-decay rate; HI_Torque; HI_T_slope; HI_Leak	Moderate: pressure, torque, or temperature may change before macroscopic leakage; cross-condition validation is limited	Possible speed reduction; pressure-difference limitation; enhanced cooling; inspect magnetic circuit, clearance, and ferrofluid distribution

Table 1. *Cont.*

Failure Mode	Dominant Operating Conditions	Intermediate Degradation Process	Leading Observable Responses	Candidate Health Indicators	Early-Warning Capability	Possible Operational or Maintenance Actions
Thermally dominated degradation	High speed; long-duration operation; insufficient cooling; elevated ambient or medium temperature	Heat accumulation; viscosity and magnetization drift; carrier-fluid loss; thermal deformation and gap redistribution	Temperature-rise-rate increase; steady-state temperature drift; torque change; pressure or differential-pressure decline; later leakage	HI_T_slope; steady-state temperature difference; normalized temperature gradient; HI_Torque; pressure-decay rate	Moderate to potentially high for persistent thermal trends; depends on sensor location and thermal boundary conditions	Possible cooling enhancement; speed/load reduction; inspect thermal path and ferrofluid condition; reassess heat-dissipation design
Liquid-medium-dominated degradation	Water, coolant, oil, or other liquid contact; pressure fluctuation; prolonged dynamic contact	Interface friction/erosion; interfacial fluctuation; barrier damage; leakage-channel formation; progressive fluid loss	AE transient; pressure fluctuation; leakage initiation; loss of watertightness; shortened life	HI_AE; pressure-fluctuation index; HI_Leak; cumulative leakage; normalized life/rotation count	Potentially high for AE-detected interface transitions; leakage alone is low/outcome-oriented; direct evidence is controlled-bench limited	Possible intensified monitoring; reduce speed or pressure difference; ferrofluid renewal; compatibility/contamination review; inspect interface
Eccentricity/disturbance-dominated degradation	Eccentricity, runout, assembly deviation, vibration, resonance, large/non-uniform clearance	Circumferential gap non-uniformity; asymmetric magnetic-pressure distribution; local weak-region growth	Vibration RMS/kurtosis/envelope variation; local pressure response; AE transient; torque fluctuation; later leakage	HI_Vib; vibration kurtosis/envelope index; normalized pressure asymmetry, if measurable; HI_Torque; HI_Fusion	Moderate: vibration may indicate disturbance before leakage; direct field validation remains insufficient	Possible alignment correction; vibration suppression; resonance avoidance; controlled start-up; inspect clearance and supports

Table 1. Cont.

Failure Mode	Dominant Operating Conditions	Intermediate Degradation Process	Leading Observable Responses	Candidate Health Indicators	Early-Warning Capability	Possible Operational or Maintenance Actions
Material and ferrofluid degradation	Long service; elevated temperature; vacuum or gas flow; oxygen or moisture exposure; incompatible sealed medium; contamination; repeated start-stop or replenishment cycles	Intrinsic property drift: carrier-fluid evaporation or volatilization; surfactant desorption or degradation; persistent agglomeration, irreversible aggregation, or sedimentation; oxidation; contamination; and compatibility-driven property drift Inventory-loss routes such as centrifugal ejection, medium extraction or erosion, and leakage should be recorded separately	Slow pressure-capacity decline; torque or temperature drift; fluid-volume loss; leakage; changes requiring fluid-property verification	Long-term HI_P_margin, HI_Torque, HI_Leak trends; exposure and inventory history; supporting offline viscosity, magnetization, dispersion, contamination, or compatibility records	Low to moderate from external online signals; material-specific identification generally requires periodic sampling or offline property measurement	Verify fluid inventory and exposure history; sample and characterize the fluid; control contamination and temperature; assess compatibility; replenish only when appropriate; partially or completely renew degraded fluid

Note: The failure mechanisms and principal physical responses synthesize direct ferrofluid-seal and foundational physical evidence. Candidate HIs, qualitative early-warning assessments, and possible actions are evidence-informed mappings proposed in this review unless direct validation is explicitly identified in the surrounding text. They are not universally validated ferrofluid-seal thresholds, sensor packages, or automatic action rules. The early-warning ratings are qualitative evidence assessments rather than universally validated performance grades: potentially high indicates that changes may precede pressure loss or macroscopic leakage, but engineering validation may be limited; moderate indicates an evolving abnormal state that is strongly affected by operating conditions or other mechanisms; low/outcome-oriented indicates that the signal mainly confirms degradation after functional performance has declined.

Each candidate HI requires seal-specific and condition-specific definition, normalization, calibration, and uncertainty assessment. The listed HIs are not intended to be summed in their raw dimensional forms.

2.6. Characterization of Performance Degradation

In addition to centrifugal, thermal, liquid-medium, and eccentricity-driven paths, intrinsic fluid and material degradation can progressively alter the properties on which the magnetization-pressure barrier depends. Its observable effects may overlap with those of operating-condition-induced degradation, so material attribution requires exposure history and, where possible, fluid-property verification. Complex operating conditions can activate different degradation pathways, but their common consequence is progressive loss of the available magnetization-pressure barrier. The resulting performance changes are expressed through reduced pressure capability, increasing leakage, abnormal temperature evolution, ferrofluid loss, and shortened useful life. These outcomes do not necessarily emerge simultaneously because their relative importance depends on speed, medium, temperature boundary, clearance, and structural conditions. Consequently, an isolated test quantity should be interpreted with its associated operating boundary rather than as a universal measure of condition. Nevertheless, progression should be assessed against the same pressure-barrier function. Table 1 consolidates the associated mechanisms, degradation manifestations, and observable quantities. The following sections use these degradation pathways as a fixed physical reference framework: Section 3 focuses on their observable manifestations, Section 4 on diagnostic and prognostic inference, and Section 5 on maintenance triggers and intervention actions.

A failure mechanism is generally not measured directly. Sensors capture the intermediate physical consequences of that mechanism, such as ferrofluid redistribution, thermal-property drift, interfacial fluctuation, clearance non-uniformity, or progressive fluid loss. For example, centrifugal migration can produce local redistribution and pressure-margin reduction before pressure, torque, or temperature changes; thermal accumulation can produce viscosity and magnetization drift; liquid-interface instability can produce transient interface motion and leakage-channel formation; and eccentricity can produce clearance and magnetic-pressure non-uniformity. The same observable signal may respond to more than one mechanism. Therefore, a mechanism-specific health indicator should combine the signal trend with the operating condition and, where necessary, complementary measurements.

3. Observable Signals, State Identification, and Health-Indicator Construction

3.1. Direct Characterization by Pressure and Leakage Signals

Pressure and differential-pressure signals are direct observations of whether a ferrofluid seal retains its available pressure margin. As detailed in Section 2, centrifugal migration and liquid-interface instability eventually affect that margin and can appear as abnormal pressure transmission or increasing leakage [1,23,24,29]. Pressure and leakage therefore provide direct operational evidence of whether the seal can still maintain its specified boundary conditions.

The interpretation of a pressure signal remains operating-condition-dependent. Under high-speed operation, a reduced pressure limit can indicate an emerging local loss of sealing capability, whereas under liquid-medium conditions, pressure changes accompanied by leakage are informative of interface-related deterioration [1,23,24,29]. Stage-wise pressure experiments in multistage seals further linked fluid properties and temperature to critical pressure, providing direct evidence that pressure measurements represent changes in sealing capacity [20].

A single pressure measurement can be insensitive or delayed relative to local weak-link formation. Combining pressure with leakage volume, life statistics, or flow-state recognition can therefore support composite indicators such as pressure margin and pressure-decay

rate. Related sealing and leakage studies have used pressure information for leakage prediction, failure-mode diagnosis, and energy-feature extraction [51–53]. For ferrofluid seals, these signals are consequently inputs to health-indicator construction rather than only performance-test outputs.

3.2. Temperature Signals for Thermally Dominated Degradation

During prolonged operation, temperature rise reflects system energy dissipation and may indicate thermally dominated degradation. Absolute temperature is strongly affected by environmental boundaries, sensor location, and transient operating conditions. A single measurement may therefore fail to reveal an early loss of thermal balance. A temperature-rise-rate health indicator can instead describe the temporal trend:

$$HI_T = \frac{dT}{dt} \quad (4)$$

where HI_T is the temperature-rise-rate health indicator, T is the temperature at the monitoring location, and t is the operating time.

Under discrete sampling conditions, Equation (4) can be written as:

$$HI_T(k) = \frac{T_k - T_{k-1}}{t_k - t_{k-1}} \quad (5)$$

Here, $HI_T(k)$ is the temperature-rise-rate indicator at sampling instant k . T_k and T_{k-1} are temperatures at instants k and $k-1$, while t_k and t_{k-1} are the corresponding sampling times.

Equations (4) and (5) define the raw temperature-rise-rate indicator HI_T . After normalization with respect to operating speed, ambient or medium temperature, and sensor location, it is denoted as HI_T_slope in Table 1 and is used later in the maintenance mapping described in Section 5.2.

The use of dT/dt is intended to describe the rate at which the seal departs from or approaches thermal equilibrium, rather than to measure material damage directly. Under a fixed operating condition and thermal boundary, a persistent positive temperature-rise rate indicates that heat generation continues to exceed heat dissipation, whereas a rate approaching zero is consistent with a steady thermal state. This interpretation is supported by direct ferrofluid-seal studies reporting time-dependent temperature evolution, speed-dependent heating, cooling effects, and thermally related performance degradation [1,17,28,42,43,49,50]. However, these studies do not establish a universal dT/dt warning threshold; HI_T_slope is therefore treated as a candidate, condition-normalized trend indicator.

Because numerical differentiation amplifies sensor noise, dT/dt should not be calculated from a single pair of noisy samples without preprocessing. It should be estimated over a predefined moving window or local linear fit after documented filtering, and the sampling interval, window length, sensor resolution, and filtering method should be reported. Start-up heating, changes in ambient or medium temperature, cooling activation, and operating-condition transitions should be modeled separately or excluded from the steady-condition baseline.

The normalization should also account for the operating phase, because the expected temperature-rise rate during start-up differs from that during steady continuous operation. A threshold calibrated for one phase or thermal boundary should not be transferred directly to another.

Several levels of evidence support the use of temperature signals. A high-speed test held 0.1 MPa at 47 m/s for 3 h, with temperature stabilizing at 39 °C [1]. This result

demonstrates short-term thermomechanical equilibrium for the tested structure and conditions. Experimental and numerical studies further show that temperature increases with rotational speed and follows condition-dependent heating and steady-state trajectories [28]. Thermal-process models link gap temperature to speed, geometry, and thermophysical properties, with higher temperatures predicted at high speed [49]. Thermal deformation can redistribute the sealing gap and alter magnetic and flow fields. Optimized cooling structures reduce local peak temperatures and improve structural reliability [43]. Inadequate heat dissipation and ferrofluid loss are also associated with high-speed failure [42]. Increasing ferrofluid thermal conductivity can reduce temperature rise and improve stability under high-speed operation [50].

The temperature-rise rate can be interpreted together with pressure decay, leakage changes, and service-life assessment only when sensor position and boundary conditions are controlled. A sustained increase may motivate condition-specific investigation of cooling, operating conditions, or the thermal path. Temperature-rise slope, steady-state temperature difference, and local temperature gradient are therefore physically supported candidate features for health-indicator construction, while single-point temperature remains sensitive to installation and environmental variation.

3.3. Torque Signals for Viscous Dissipation and Start-Up Stability

Torque or frictional torque is a measurable auxiliary signal for ferrofluid-seal condition monitoring. It reflects changes in flow resistance, viscous dissipation, and start-up stabilization and can therefore complement pressure and temperature measurements when identifying changes in operating state.

Torque is sensitive to ferrofluid-seal operating conditions. In a hybrid lip seal with local ferrofluid lubrication, simultaneous torque, temperature, and pressure measurements quantified changes in sealing performance [3]. Durability studies also linked stable hybrid-seal operation to magnetic-field strength and ferrofluid viscosity [54]. Torque therefore reflects energy loss and can indirectly indicate changes in rheology and lubrication.

During start-up, torque can reveal transient ferrofluid redistribution and stabilization of the shaft-seal system. Tests compared fixed-speed, fixed-torque, and variable-torque start-up modes [32]. The modes produced distinct torque and speed fluctuations, while field strength and pole-tooth number affected torque amplitude and slope [32]. Variable-torque start-up reduced fluctuation amplitude and improved stability. Torque can therefore indicate viscous dissipation, increased flow resistance, redistribution, and abnormal start-up behavior.

For online monitoring, torque maps changes inside the gap to a response outside the shaft system. It can complement pressure and temperature measurements when early flow anomalies, increased resistance, or start-up instability are suspected. Torque is thus most useful as an auxiliary indicator in a multisource monitoring framework.

3.4. Vibration Responses to Eccentricity and Local Abnormalities

Vibration signals are especially useful for capturing local anomalies and dynamic disturbances in ferrofluid seals. They can support early warning and robustness assessment when eccentricity, assembly deviation, uneven clearance, or local friction is present. As detailed in Section 2.4, eccentricity and clearance non-uniformity alter the magnetic and pressure fields; from a monitoring perspective, the key question is whether these disturbances produce detectable vibration responses. Experimental and design studies indicate that vibration-sensitive features can reveal loss of operating stability and that structural adaptation can improve resistance to vibration environments [26,44].

Transferable sealing studies show that vibration can influence leakage and degradation. In reciprocating seals, vibration modulates the gap and contact state, with leakage peaking

near resonance [45]. Mechanical-seal studies also show increasing vibration-sensitive features as sealing-surface performance deteriorates, enabling early warning [55]. For ferrofluid seals, RMS, kurtosis, and envelope features may track the development of local anomalies.

Vibration signals are useful auxiliary indicators of eccentricity-related local anomalies and dynamic disturbance. RMS, kurtosis, and envelope features should be interpreted with awareness of external mechanical noise and operating-condition dependence; combining them with other measurements improves abnormal-state identification.

3.5. Acoustic-Emission Signals for Early Fault Identification

Acoustic-emission signals can capture transient changes before a large pressure drop or macroscopic leakage is evident, making them valuable for early fault identification and state-transition monitoring. The interface-instability mechanisms that can generate such responses are detailed in Section 2.3; this section focuses on their measurable high-frequency manifestation.

Acoustic emission shows strong potential for identifying ferrofluid-seal states. Denoising and image-based feature extraction improved state-classification accuracy and resistance to Gaussian noise [30]. Another study used pressure-assisted labels to distinguish no-flow, one-stage flow, and two-stage common-flow states [31]. Time- and frequency-domain features enabled accurate classification. Acoustic emission may therefore support both anomaly detection and staged recognition as a seal transitions from stable to abnormal operation.

Evidence from related sealing studies also shows that acoustic-emission signals can capture degradation within short time windows. Seal wear classification based on acoustic-emission features and neural networks can achieve high-precision identification within a short time window [33]. Time-series prediction based on ARIMA models and AE features can further extrapolate trend changes before seal failure, providing a basis for early maintenance decisions [34]. In addition, studies on liquid-film seal friction monitoring show that appropriate signal processing helps acoustic-emission signals retain friction-state information for state recognition at different operating stages [56]. Together, these studies indicate that acoustic-emission signals have strong potential for short-term identification, early warning, and trend extrapolation.

Acoustic-emission features are sensitive to environmental noise and signal-processing choices. They are therefore best used as high-sensitivity auxiliary channels and interpreted with pressure, temperature, or vibration information. Their principal value is early warning of a state transition rather than replacement of the other monitoring signals.

Table 2 compares the monitoring roles, sensor locations, and suitable operating scenarios of the principal observable signals.

Table 2. Sensor-selection guidance and recommended multisource combinations for ferrofluid-seal monitoring.

Signal/Record Type	Typical Location	Monitoring Role	Complementary Signals	Early-Warning Role	Applicable Conditions	Main Limitations
Pressure/differential pressure	Seal cavity, interstage, upstream/downstream channel	Pressure-margin change and abnormal pressure transmission	Leakage for confirmation; temperature and torque for high-speed/thermal interpretation; AE for interface transitions	Moderate: direct pressure-margin measure; may be delayed for highly local weak regions	High speed; high pressure difference; liquid contact; continuous operation	Pipeline dynamics, sampling delay, and clogging; condition-specific baseline required

Table 2. Cont.

Signal/Record Type	Typical Location	Monitoring Role	Complementary Signals	Early-Warning Role	Applicable Conditions	Main Limitations
Leakage	Outlet, collection end, downstream measurement	Functional confirmation, failure definition, and life assessment	Pressure and AE; operating history and medium-condition record	Low/outcome-oriented alone; useful for failure confirmation and life definition	Liquid contact; leakage-path monitoring; long-duration service	Often lags local degradation; collection design and medium properties affect measurement
Temperature	Housing, bearing seat, near clearance area	Thermal accumulation, property drift, and thermal-coupling response	Torque and pressure; speed plus ambient/medium-temperature records	Moderate to potentially high for persistent trends; sensor position and thermal boundary are critical	High speed; insufficient cooling; elevated ambient/medium temperature; long duration	Does not directly resolve local gap temperature; strongly environment dependent
Torque	Drive shaft end, rotor side, near coupling	Viscous dissipation, flow resistance, friction state, and start-up stability	Temperature and speed record; pressure at high speed; vibration during start-up abnormalities	Moderate after speed-, load-, and temperature-baseline compensation	Start-up/transient operation; high-speed rotation; friction or flow-resistance change	External load coupling and acquisition accuracy can confound interpretation
Vibration	Shell, end cover, bearing seat; runout sensor when available	Eccentricity, local instability, structural disturbance, and collision anomalies	Pressure, AE, and torque; shaft displacement/runout when available (engineering recommendation)	Moderate for eccentricity/disturbance; may precede leakage	Eccentricity, runout, vibration, resonance, large clearance, start-up	External machine/bearing noise; direct ferrofluid-seal field validation is limited
Acoustic emission (AE)	Shell near sealing area and end cover	Interface instability, microleakage initiation, local friction, and state transition	Pressure for state labeling; leakage for confirmation; vibration to separate structural disturbance	Potentially high for transient interface change; direct bench evidence exists, but field robustness is unresolved	Liquid contact; early interface anomaly; local friction; controlled bench monitoring	Noise sensitive; feature engineering, sensor coupling, and model robustness are critical
Operating history and accumulated-life record	Synchronized system, maintenance, and test records	Degradation context, RUL modeling, threshold calibration, and failure-event definition	All synchronized sensor data plus speed, pressure difference, medium, maintenance, and failure records	Not an independent real-time early-warning channel; essential for RUL and calibration	Long-duration aging, contamination, liquid-medium service-life analysis, RUL studies	Requires consistent event definitions and record quality; not independently diagnostic

Note: Direct ferrofluid-seal evidence supports pressure, leakage, temperature, torque, and AE observations under specific experimental arrangements. AE-pressure state labeling has direct ferrofluid-seal bench evidence. Vibration-based diagnostic features and several complementary-signal strategies rely partly on transferable evidence. Sensor packages and multisource combinations not explicitly demonstrated in one ferrofluid-seal experiment are presented as proposed engineering configurations. Sensor selection should be risk-driven, and the benefit of additional channels must be evaluated against synchronization, installation, noise, and computational requirements. AE = acoustic emission; RUL = remaining useful life.

3.6. Health-Indicator Construction and State Representation Framework

The evidence maturity differs between observable signals and the derived health-indicator framework. Pressure, leakage, temperature, torque, and AE have direct ferrofluid-seal measurement or state-recognition support under specific test conditions. Vibration-based fault features, some leakage diagnostic methods, and time-series prognosis are supported mainly by transferable sealing or mechanical-system studies. The unified HI names, condition-normalization rules, multisource combinations, and mechanism-to-action mappings introduced here are candidate formulations that still require direct cross-condition and run-to-failure validation for ferrofluid seals.

Each candidate HI has a distinct evidence basis and maturity level. HI_T_slope is a physically supported trend feature: direct ferrofluid-seal studies report time-dependent temperature evolution, speed-dependent heating, cooling effects, and thermally related performance changes [1,17,28,42,43,49,50], but they do not validate a universal slope threshold or cross-structure HI. HI_P_margin is a physics-informed candidate derived from the magnetization-pressure relation, operating differential pressure, and structure–performance or operating-boundary studies [4–6,10,20,29,57–62]; its value depends on the uncertainty of the capacity baseline and is not an experimentally universal safety margin. HI_Leak has direct relevance to loss of watertightness, functional failure, and service-life assessment [18–25,27,41], whereas leakage diagnosis and prognostic methods from other sealing systems are transferable evidence [51–53,63–65]; it is often outcome-oriented rather than the earliest warning signal. HI_AE has direct bench-scale ferrofluid-seal state-recognition evidence [30,31], but universal AE-energy thresholds, cross-rig thresholds, and RUL mappings remain unvalidated. HI_Vib is physically relevant to eccentricity, clearance, and vibration environments [26,44], while most diagnostic features are transferable from related rotating systems [45,55,66–68] and require compensation for background vibration. HI_Torque is supported by seal torque, friction, viscous-dissipation, and start-up observations [3,17,32,54], but external load, bearings, and drive torque must be separated or compensated. HI_Fusion has not yet been directly validated as a fused health indicator for ferrofluid seals. Study [31] provides direct evidence for AE-based state recognition with pressure-assisted state labeling; pressure was used to assist the definition of the state labels rather than being fused with AE as an input health indicator. The complete condition-normalized fusion formula, normalization maps, weights, thresholds, and cross-condition interpretation in Equation (6) are therefore author-proposed formulations requiring direct validation. Accordingly, direct measurement of a raw signal does not validate a common normalization, threshold, or fusion weighting across seal structures and operating conditions.

For material and ferrofluid degradation, online pressure, temperature, torque, and leakage signals are indirect manifestations rather than mechanism-specific diagnoses. They cannot independently distinguish carrier-fluid evaporation, surfactant deterioration, persistent aggregation, oxidation, contamination, or incompatibility. Where material-state attribution is required, periodic or event-triggered records should include, as appropriate, ferrofluid inventory or mass/volume change, viscosity or rheological response, a magnetization curve or saturation magnetization, particle-size or agglomeration indication, sedimentation or phase-separation stability, water or contaminant content, interfacial-tension or compatibility results, and sampling, replenishment, and replacement history. External online signals may indicate that the ferrofluid state has changed, but they do not uniquely identify the underlying chemical or colloidal mechanism. Material-level attribution generally requires a documented sample, reference measurement, and exposure history.

Where electrical access and application compatibility permit, periodic dielectric spectroscopy may provide complementary information on field-dependent polarization, particle structuring, and temperature-sensitive material response in oil-based ferrofluids [39]. It should currently be treated as an offline or periodic material-characterization candidate

rather than a validated online ferrofluid-seal health indicator. Its interpretation would require a seal- and formulation-specific baseline, frequency selection, temperature compensation, electrode-geometry control, and separation of reversible field-induced structure from persistent material degradation.

Health-indicator construction transforms raw monitoring data into interpretable quantities for condition identification and service-life prediction. The workflow proceeds from signal conditioning and feature extraction to indicator construction and state representation. Denoising, time synchronization, and normalization to the operating condition are essential because noise, sensor placement, and boundary variation can otherwise be mistaken for degradation. Feature extraction should remain traceable to sensor bandwidth, sampling window, and the relevant operating condition. The same preprocessing rules should be recorded so that later diagnostic results can be reproduced and compared across seals or test rigs. Table 2 summarizes candidate observable signals and their practical arrangements.

A useful indicator should retain a clear physical meaning, be measurable with the available sensing arrangement, and exhibit a trend that is robust enough for state assessment. Selection should also consider measurement reliability, sensitivity over the expected operating range, and susceptibility to installation variation. The mechanism-specific signal candidates are introduced in Sections 2 and 3; health-indicator construction should preserve this connection without treating an arbitrary statistical feature as evidence of degradation.

Transferable sealed-system studies show that useful indicators are measurable, monotonic where possible, and linked to a functional threshold. Reliability models for hydraulic and piston-rod seals have used degradation parameters or leakage as state variables [63,64], while coolant-pump leakage studies have used geometric and leakage features to distinguish modes and estimate remaining useful life [65]. Across studies, the signal source, data split, failure criterion, and condition coverage must be considered when judging whether a candidate is useful beyond one test. Feature dimension alone is not a sufficient criterion for a health indicator.

For ferrofluid seals, the state-representation pipeline is signal preprocessing, feature extraction, health-indicator construction, and state recognition. After denoising, synchronization, and condition normalization, physically meaningful features can be fused into indicators that distinguish normal, degraded, abnormal, and imminent-failure intervals [69,70]. Thresholds and state intervals should be tied to documented operating boundaries rather than selected only to maximize separation in one dataset. Priority should be given to physical consistency, cross-condition comparability, and trend monotonicity so that the resulting representation can support the diagnostic and prognostic methods in Section 4.

To make the mapping operational, the following quantities are candidate health indicators rather than universal standards. HI_T_slope is the condition-normalized temperature-rise rate. HI_P_margin is the normalized difference between estimated available sealing-pressure capacity and the applied operating differential pressure. HI_Leak is the normalized leakage rate or cumulative leakage relative to a functional-failure criterion. HI_AE represents condition-normalized AE energy, feature trend, or calibrated abnormal-state probability. HI_Vib represents condition-normalized vibration RMS, kurtosis, envelope feature, or a physically justified fusion. HI_Torque is torque deviation from a speed-, load-, and temperature-specific baseline. HI_Fusion is an author-proposed, condition-normalized candidate composite representation based on complementary single-domain HIs, not a universally validated ferrofluid-seal state variable.

Their normalization, baselines, and thresholds—and the fusion weights where applicable—must be calibrated for the seal structure and operating condition; no HI should be interpreted independently of speed, pressure difference, medium, temperature, cooling state, and operating phase. The resulting engineering mapping is operating

condition and failure mechanism to intermediate degradation process, observable response, condition-normalized feature, health indicator, diagnosis/prognosis, and possible operational or maintenance action. This mapping is not one-to-one: a signal may respond to several mechanisms, and a mechanism may require several complementary signals for reliable interpretation.

For any candidate HI, the normalization mapping should remove unit differences, align direction so that a larger normalized value denotes greater severity or risk, account for the principal condition effects on the healthy baseline, and preserve the meaning of a functional boundary where one exists. The mapping may be based on healthy-condition mean and standard deviation, median and robust scale, quantile range, a documented warning or functional-failure boundary, or a calibrated physical response model such as a pressure-capacity, thermal, speed-load, or structural-response baseline. A raw pressure margin, for example, decreases as risk rises and must therefore be directionally transformed before fusion. No single normalization method is universally appropriate. The selected mapping must be defined from training or calibration runs, fixed before testing, and reported together with its valid operating range; it must not be estimated from the complete dataset including held-out test data.

A transparent calibration workflow begins by defining the engineering task—state recognition, early warning, diagnosis, RUL, or maintenance triggering—and by assigning independent run-level training, validation, held-out-condition test, and, where available, external-rig partitions. Healthy baselines, scales, operating-condition corrections, candidate weights, and warning or failure thresholds are estimated only from calibration, training, and validation runs. Thresholds must be linked to documented pressure loss, leakage, loss of watertightness, a temperature boundary, or another functional or risk criterion rather than selected solely to maximize classification accuracy. The model is then frozen and evaluated on unseen runs or conditions for discrimination, false alarms, missed detections, monotonicity, threshold lead time, uncertainty calibration, and maintenance relevance.

Uncertainty arises from sensor resolution, calibration drift, mounting variation, noise, synchronization error, derivative estimation, finite window length, filtering, missing data, limited healthy runs, condition mismatch, baseline-model error, correlated indicators, alternative weight solutions, uncertain failure thresholds, individual seal variation, and degradation-path variability. A fused point score alone is insufficient. Measurement, normalization, and weight uncertainty should be propagated through repeated-run bootstrap, Monte Carlo sampling, Bayesian estimation, or another justified method, with the selected assumptions reported. Results should include a confidence or credible interval, repeated-run variation, or another uncertainty range; inputs outside the calibrated range should produce reduced confidence, abstention, or recalibration rather than an unjustifiably confident health state.

4. Diagnosis and Remaining Useful Life Prediction Methods

To further illustrate the basic logic of ferrofluid-seal state assessment, Figure 3 summarizes the relationship between observable signals, health-indicator construction, and diagnostic and prognostic tasks.

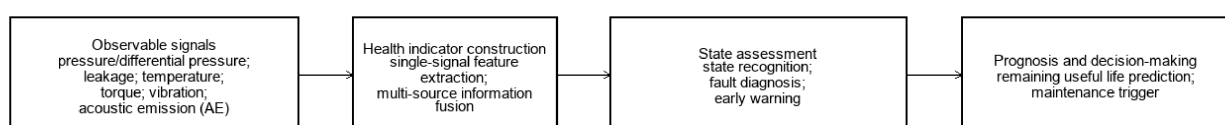


Figure 3. Framework of relationships among observable signals, health indicators, and diagnosis/prognosis tasks.

The observable signals entering Figure 3 are not selected independently of the failure physics. They are the measurable outputs of the intermediate degradation processes mapped in Table 1, and their recommended sensing configurations are summarized in Table 2. Health-indicator construction then transforms these condition-dependent responses into representations suitable for diagnosis and prognosis.

Raw pressure, leakage, temperature, torque, vibration, and acoustic-emission signals are not direct measures of seal health. They require feature extraction, health-indicator construction, and state mapping before supporting diagnosis, degradation assessment, or RUL prediction. Ferrofluid seals are governed by coupled magnetic, thermal, fluid, and structural processes. State assessment therefore requires a structured mapping from failure mechanisms to observable features, health representations, and diagnostic or prognostic inference. Section 4 reviews health-indicator use, mechanism-based diagnosis, data-driven diagnosis, multisource fusion, and RUL prediction.

4.1. Health Indicators and Their Roles in Diagnosis and Prognosis

A health indicator (HI) connects raw monitoring data to fault diagnosis and remaining useful life prediction. Its purpose is to provide a stable representation of degradation stage and failure risk despite non-stationary, condition-dependent observations [71,72]. For engineering prognosis, an HI should be measurable, physically interpretable, sufficiently monotonic for the intended task, and associated with a definable failure threshold.

The mechanism-specific candidates and observable signals are summarized in Sections 2 and 3 and in Tables 1 and 2. Here, the emphasis is on their use for diagnostic state separation and prognostic threshold modeling.

For fault diagnosis, HIs improve the stability and interpretability of state separation. They reduce the influence of operating-condition fluctuation, sensor position, and noise on direct classification and can support normal, early-degradation, significant-degradation, and imminent-failure intervals [63–65,69,70]. Their value lies in producing state distinctions that remain meaningful for an engineering decision rather than merely increasing a classifier score.

For remaining useful life prediction, HIs are the state variables used to model degradation trajectories and threshold crossing. Reliable extrapolation requires a trend that is sufficiently monotonic, adaptable across operating conditions, and paired with an explicit threshold and uncertainty treatment [64,65,70,71]. The quality of HI construction therefore sets an important limit on the credibility of subsequent prognostic results.

Current ferrofluid-seal studies still rely heavily on single-domain features and empirical thresholds from individual test conditions. Future indicators should be evaluated for cross-condition comparability, long-term trend stability, and physical consistency under changes in speed, pressure difference, medium, and temperature. This shift is necessary for HIs to provide unified support for diagnosis, prognosis, and the maintenance decisions considered in Section 5.

4.2. Mechanism-Based Fault Diagnosis Methods

Mechanism-based diagnosis uses magnetic-field, pressure-transmission, fluid-boundary, and structural-stress models to establish a healthy response baseline. Abnormal states are then identified through parameter deviations, residual changes, or the localization of weak regions. Unlike data-driven classification, this approach addresses how failure develops and where anomalies first emerge. Its principal advantages are physical interpretability, traceability, and direct relevance to design feedback.

For ferrofluid seals, mechanistic diagnosis uses the Section 2 physics to define a normal response and identify deviations in the pressure barrier, interface condition, or operating boundary. Force-balance and operating-boundary analyses can identify when

excessive pressure difference, rotational speed, or vibration is likely to produce an abnormal response [57]. Earlier independent modeling incorporated free-surface shape, particle diffusion, and the competing effects of magnetic, capillary, and pressure forces when evaluating static seal stability [21].

Finite-element, multiphysics, and parameter-mapping studies provide a basis for identifying local failure mechanisms in ferrofluid seals. Response-surface analysis of sandwich magnetic circuits links geometric parameters to magnetic-field distribution and pressure capacity [58]. These parameter–performance maps can help identify structural anomalies and performance deviations. Studies of staggered pole teeth show that pressurization failure progresses through microleakage, local barrier weakening, and complete leakage [59,60]. This staged behavior supports mechanism-based identification of failure progression. Helical-tooth studies further show that tooth angle alters magnetic flux, gap pressure, and velocity distributions [61]. Such models can explain performance differences and identify structural parameters associated with local instability.

Studies of special operating conditions and combined structures also inform mechanism-based diagnosis. Simulations and experiments on ferrofluid-sealed pressure-vessel safety valves link gap, groove width, tooth height, excitation, and sealing capacity [62]. These relationships can define a calibrated baseline between structural and excitation parameters and sealing pressure. Persistent deviation from this baseline could indicate gap anomalies, magnetic-circuit degradation, local ferrofluid loss, or parameter mismatch. Mechanistic models thus provide a theoretical healthy response for online diagnosis and reduce reliance on empirical thresholds.

The ferrofluid-seal studies cited in this subsection directly validate mechanism, operating-boundary, and structure–performance relationships. They do not, by themselves, validate an online residual-diagnosis pipeline. Their use as calibrated diagnostic baselines, weak-region localization tools, or fault-decision rules is therefore treated as a proposed mechanism-based diagnostic pathway unless a study explicitly evaluates the diagnostic task.

Broader PHM studies show that physics-based diagnostic models can support anomaly detection and fault isolation in complex equipment [73]. They help identify which physical quantity deviates first and which fault is the likely source. This capability is important for ferrofluid seals because degradation couples magnetic, thermal, fluid, and structural processes. A binary normal/abnormal result rarely supports specific actions such as speed limitation, cooling, replenishment, or structural adjustment.

Mechanism-based diagnosis nevertheless has clear limitations. Models depend on boundary conditions, material parameters, and simplifying assumptions. They may not capture contamination, aging, random disturbances, or assembly errors during service. Mechanistic models also struggle to represent long-term statistical variation and unit-to-unit differences under complex liquid-medium conditions. They are strongest at explaining causes and locating weak regions, but less adaptable than data-driven methods for rapid cross-condition classification. Accordingly, they should provide the physical baseline and explanatory framework, not replace data-supported diagnostic methods.

4.3. Data-Driven Fault Diagnosis Methods

Compared with mechanistic-model diagnosis, data-driven fault diagnosis learns state modes and fault categories from monitoring signals without first establishing a complete magnetic, thermal, flow, and structural coupling model. For ferrofluid seals, acoustic emission, pressure, temperature, and vibration can provide complementary indicators of interface changes and degradation. However, reported accuracy is interpretable only together with the object, class definition, dataset construction, data split, validation protocol, and comparator. The evidence below therefore distinguishes direct ferrofluid-seal studies from transferable studies on other sealed or rotating systems.

The available direct ferrofluid-seal evidence is promising but remains limited in scale. Dai et al. [30] classified no-leakage, microleakage, and complete-leakage states of a two-stage ferrofluid seal from acoustic-emission high-order-cumulant images. From 401,185 acquired acoustic-emission samples, 1500 images (500 per class) were selected and randomly divided 4:1 into 400 training and 100 test images per class. The original study reports internally inconsistent overall test accuracy values: Table 1 gives 98.00% (294/300), whereas the accompanying text states 98.67%. The reported class-wise precision, recall, and F1 values are 97–100%. Therefore, this result should be interpreted as a high within-dataset recognition result from a single experiment rather than as an exact external benchmark [30]. Xue et al. [31] used acoustic-emission features and pressure-assisted labels for three flow states of an oil-based ferrofluid seal. Their 9330 samples were divided 2:1 into 6220 training and 3110 test samples; the GWO-RF model reported 92.32% average test accuracy and F1 values of 97.16%, 92.07%, and 87.84% for the three states. These results demonstrate feasibility for bench-scale state recognition, not yet condition-independent diagnostic performance.

Transferable evidence illustrates both the potential and the limits of current learning pipelines. In a hydraulic piston-rod seal study, acoustic-emission features from unworn, semi-worn, and worn states were split 70/15/15 for training, validation, and testing; a downsampled SCG-ANN reported 99.3% test accuracy, while selected SVM results were also reported for comparison [33]. For centrifugal pumps, a SobelEdge-scalogram CNN that included mechanical-seal fault classes reported 99.68% accuracy, 99.65% precision, 99.68% recall, and 99.66% F1 under an 80/20 split with five-fold validation [74]. A DCNN study of monoblock pumps reported 99.07% validation accuracy after a 70/30 split and a 34 s training time for 30 epochs [75]. Because these objects, signal chains, and operating conditions differ from ferrofluid seals, their numerical metrics should be treated as method-transfer evidence rather than as ferrofluid-seal benchmarks.

Cross-condition validation is particularly important because rotational speed, pressure difference, medium, and temperature can shift the signal distribution of a ferrofluid seal. In ship-pipeline valve leakage diagnosis, Liu et al. [76] used acoustic-emission time-frequency images from three pressure conditions, an 80/20 split, six source-target transfer tasks, and ten repeated tests per task. Their MK-MMD-MCFCNN reported 99.37% average accuracy, compared with 57.12% for CNN, 63.09% for MCFCNN, and 86.35% for MMD-MCFCNN. This is a more informative validation design than a single random split, but it still requires target-condition data and is not seal-specific. Similar transferable work should be used to design ferrofluid-seal protocols with held-out speeds, pressures, temperatures, media, structures, and ideally an independent test rig.

Additional transferable studies have investigated AE-based cross-condition leakage diagnosis in valves and data-driven start-stop, friction-state, abnormal-condition, and wear diagnosis in mechanical seals [77–81].

The reported metrics are not directly rankable across studies. Accuracy can be inflated by class imbalance, and adjacent time windows from one experiment can leak highly correlated signal content into random training and test subsets. For multi-state diagnostics, class-wise precision, recall, and F1, confusion matrices, class balance, and the exact split unit should be reported together; for early-warning tasks, lead time and false-alarm burden should be reported. A model should additionally be tested under deliberately held-out operating conditions and, where possible, on another rig or seal structure. Computational cost also matters for online deployment: training time, inference latency, memory use, sensor sampling rate, and synchronization overhead remain rarely reported for ferrofluid-seal studies.

Although the studies cited in Sections 2 and 4 establish important ferrofluid-seal mechanisms and operating boundaries, their experimental configurations, operating conditions, failure criteria, measured signals, duration, and repetition structures differ substantially.

High-speed studies emphasize pressure resistance, temperature, and fluid loss [1,17,42]; water-environment and replenishment studies emphasize leakage, service life, and interface protection [18,23–25]; eccentricity work may be numerical rather than physical testing [26]; and thermal, start-up, and visualization studies address specific response mechanisms [28,32,41]. The two direct state-recognition studies use bench-scale labels and signals rather than run-to-failure trajectories [30,31]. Table 3a therefore records only source-reported experimental facts and explicit NR entries, whereas Table 3b distinguishes direct ferrofluid-seal diagnosis evidence from transferable diagnostic and prognostic evidence. This separation is necessary because pressure capacity, leakage onset, thermal response, and classification metrics do not constitute interchangeable reliability outcomes.

Table 3. Quantitative comparison of representative primary studies relevant to ferrofluid-seal reliability. (a). Experimental configurations, operating conditions, failure criteria, and measured outcomes in direct ferrofluid-seal studies. (b). Diagnostic and prognostic performance and validation characteristics of representative studies. The experimental context of representative direct ferrofluid-seal studies is summarized separately in (a). Diagnostic metrics should be interpreted with the dataset construction, split unit, operating-condition coverage, and study object.

Ref.	Fluid and Medium	Seal Configuration	Operating Conditions	Test Duration/Trajectory	Failure/State Criterion	Measured Signals	Quantitative Outcome	Main Limitation
(a)								
[1]	MF data NR; air	Rotary poles; 0.10 mm gap.	30,000 rpm; 47 m/s; 0.10 MPa; cooling-water temperature: 3 °C	3 h.	Pressure hold; leakage rule NR.	P; speed; temp.	At 30,000 rpm (47 m/s), 0.10 MPa held for 3 h; final temperature 39 °C.	One case; repeats; leak metric NR.
[17]	MF; medium NR	Motor-shaft MFS.	556–2897 rpm; roughness 0.357–7.21 µm; ambient +50 °C.	NR.	No failure test.	Torque; temp.	At 2897 vs. 556 rpm: temp. up to 2.0× and torque up to 2.2×; roughness 0.357–7.21 µm: temp. +20%, torque +55%. Quantitative outcome NR; qualitative finding: critical pressure, velocity, and working life were compared among fluids.	Not failure; RUL not assessed; runs NR.
[18]	Four silicone MFs; water	Dynamic MFS; geom. NR.	Water; P and speed varied.	Life paths; duration NR.	Loss of tightness; leakage.	Critical P; velocity; life.	Quantitative speed–pressure–rotation–life relationship reported; common coefficient NR.	No cross-rig diagnostic validation.
[23]	FLS040.040 and two FLA formulations (FLA002.25, FLA003.45); water	One stage; 50 mm; 14 magnets; gap 0.10 mm.	Water; P and speed varied.	N to leakage; 10 s to >10 h.	Leakage.	Water P; speed; N.		Preliminary; no diagnosis; no RUL.
[24]	Magnetite MF; water	3 stage N38; 50 mm; gap 0.20 ± 0.05 mm.	0–1500 rpm; 5 kPa; T ≤ 40 °C.	Tested to failure or censored at 48 h; the 48 h run corresponded to 4.32 million rotations without failure.	Water in leakage channel.	3 P; speed; time; flow; leak.	Static P 3.8–5.9 kPa (high Ms).	One rig; no online diagnosis; no RUL.

Table 3. Cont.

[25]	MF data NR; water	Two rotary seals; 100 µm gap; replenishment.	Static and dynamic tests; condition matrix NR.	Life tests; duration NR.	Capacity below required P.	Capacity; life; replenishment.	Quantitative outcome NR; qualitative finding: replenishment extended and controlled service life in the tested pressurized-water seal. Quantitative outcome NR; qualitative finding: thermal response changed with heating power and solid content.	Device specific; no cross-rig validation; no RUL.
[28]	MF; medium NR	MF in sealing gap; geometry NR.	Rotational speed, heating power, and solid content varied.	Thermal tests; duration NR.	Thermal response.	Temp.		No functional failure; no RUL.
[30]	MF; medium NR	Two-stage MFS.	Case; sensor location NR.	1500 AE images (500/state); 4:1 random split; physical acquisition duration and independent experimental runs NR 9330 signal samples; 2:1 train/test split; ten repeated model evaluations; physical acquisition duration and independent experimental runs NR.	No-leakage, microleakage, and complete-leakage labels.	AE input; leakage-state labels.	Table 1: 98.00% (294/300); text: 98.67%; class metrics: 97–100%.	One rig; random split; no RUL.
[31]	Oil MF; medium NR	Static two-stage pole shoe.	P, geometry, and sensor location NR.		Three flow states.	AE; pressure-assisted state labels.	Accuracy 92.32%; F1 97.16%, 92.07%, and 87.84%.	State recognition; no input fusion; no RUL.
[32]	MF; medium NR	Rheometer start-up.	Field strength, pole teeth, and torque varied.	Start-up; duration and runs NR.	Start-up response.	Torque; speed.	Quantitative outcome NR; qualitative finding: variable torque produced slower speed rise and a smaller fluctuation range.	No seal failure; no RUL.
[41]	MF; medium NR	Polymagnetic shaft seal; visualization.	P > 70% maximum; gap 0.4–0.6 mm; speed varied.	Life and self-healing; duration NR.	Leakage; no second P capacity; failure.	Interface; P; speed; life.	Self-healing ≤0.4 mm; failure > 1000 rpm	One configuration; no diagnosis/RUL.
[42]	Ester MF; medium NR	High-speed MFS; geometry NR.	To 9000 rpm; cooled and uncooled.	Duration and runs NR.	Ferrofluid ejection; loss.	Sealing-gap temp.; speed; loss.	Ferrofluid ejection at circumferential speed ≈ 13.7 m/s; sealing-gap temperature 92 °C at 9000 rpm.	Duration; runs; RUL NR.

Table 3. Cont.

Ref- erence	Evidence type	Object and signal	Method/task	Dataset and validation	Reported quantitative performance	Baseline or comparison	Main limitation
(b)							
[30]	Direct ferrofluid-seal evidence	Two-stage ferrofluid seal; AE high-order-cumulant images; no-leakage/microleakage/complete-leakage.	VGG16 state classification.	1500 images (500/class); 4:1 random train/test split (400/100 per class); the training subset was further divided into training and validation data at a 9:1 ratio.	Overall accuracy is internally inconsistent in the original study: Table 1 reports 98.00% (294/300), whereas the text reports 98.67%; class-wise precision, recall, and F1 = 97–100%.	NIN, GooLeNet, and ResNet50.	One failure experiment; random split; no external or different-structure validation; internally inconsistent reported overall accuracy.
[31]	Direct ferrofluid-seal evidence	Static two-stage oil-based ferrofluid seal; AE with pressure-assisted labels; three flow states.	GWO-RF classification.	9330 samples (1543/5261/2526); 2:1 train/test (6220/3110); ten repeated model evaluations.	Average test accuracy 92.32%; F1 97.16%, 92.07%, and 87.84% for the three states.	GWO parameter optimization; no unoptimized-RF test result reported.	Static one-rig data; adjacent time segments; no independent or cross-condition test.
[33]	Transferable evidence	Hydraulic piston-rod seal; AE; unworn/semi-worn/worn states.	SCG-ANN wear classification.	Downsampled 16×1200 feature data; 70/15/15 training/validation/test; four pressure levels (10–40 bar), one rig.	Test accuracy 99.3%; class accuracies 99.9%, 100%, and 98.8%.	Earlier SVM results reported 99.4% and 98.1% for two classes.	Same test rig and within-dataset split; no external validation; not a ferrofluid seal.
[34]	Transferable evidence	Hydraulic piston-rod seal; AE RMS time series.	ARIMA failure forecast/RUL-related prediction.	Four run-to-failure tests; 15 pre-samples fitted and the next 10 samples forecast.	RTF1: RMSE = 0.187 mV, MAPE = 20.26%; RTF2: RMSE = 0.326 mV, MAPE = 28.99%; RTF3: RMSE = 0.053 mV, MAPE = 4.95%; RTF4: RMSE = 0.104 mV, MAPE = 8.88%.	ARIMA orders compared; no common baseline reported (NR).	Only four run-to-failure tests; performance varied markedly among runs and deteriorated under variance shifts or weak temporal correlation; no cross-rig validation; not a ferrofluid seal.
[55]	Transferable evidence	Mechanical-seal face vibration.	SVDD one-class early fault detection.	800 normal samples for training; 3200 samples from four experiments.	The source reports incipient-fault detection before the designated failure sample, but the stated lead times of 10.5 and 12 ‘months’ are internally inconsistent with the plotted sampling interval of 10 s per sample. A reliable quantitative lead time therefore cannot be determined.	One-class SVDD; conventional classification baseline NR.	Internally inconsistent time unit; quantitative lead time is not treated as validated; early-warning rather than point-RUL evidence; no external field validation.

Table 3. Cont.

[76]	Transferable evidence	Ship-pipeline valves; two-sensor AE time-frequency images.	MK-MMD-MCFCNN cross-domain leakage diagnosis.	Three pressure conditions; 80/20 split; six transfer tasks; ten repeated tests/task.	Average accuracy 99.37%.	CNN 57.12%; MCFCNN 63.09%; MMD-MCFCNN 86.35% average accuracy.	Requires target-condition data; not seal-specific.
[74]	Transferable evidence	Centrifugal-pump vibration; four states including mechanical-seal hole and scratch.	SobelEdge-scalogram CNN fault classification.	80/20 split with five-fold validation.	Accuracy 99.68%; precision 99.65%; recall 99.68%; F1 99.66%.	Two published reference models compared in the study.	Pump dataset, not ferrofluid; external-rig and cross-condition evidence not reported.
[75]	Transferable evidence	Monoblock centrifugal pump; current/vibration images; healthy, impeller, and mechanical-seal fault classes.	DCNN classification.	16,384 samples; 11,468 training and 4916 test samples; 70/30 split.	Validation accuracy 99.07%; training time 34 s for 30 epochs.	Independent baseline comparison NR.	Random within-dataset split; not a ferrofluid-seal study.

(a) Note: NR = not reported in the source. Values are reproduced from original primary studies; quantities were not inferred from schematic drawings. Test duration, rotation count, signal-sample count, model evaluations, and number of independent physical runs are reported separately where available. Quantitative outcomes are not directly rankable across different ferrofluid formulations, seal geometries, media, operating conditions, and failure criteria. MF = magnetic fluid; MFS = magnetic-fluid seal; P = pressure; T/temp. = temperature; AE = acoustic emission. (b) Note: AE, acoustic emission; CNN, convolutional neural network; RF, random forest; F1, F1 score; RMSE, root mean square error; NR, not reported; RUL, remaining useful life; RTE, run-to-failure; GWO, grey wolf optimizer; SVDD, support vector data description; MMD, maximum mean discrepancy. Direct ferrofluid-seal evidence indicates that the diagnostic task was evaluated on a ferrofluid-seal object. Transferable evidence indicates that the method was evaluated on another sealing or rotating-mechanical system. Proposed methods without published quantitative validation are not listed as performance studies in this table.

The primary-study record in Table 3a constrains how the results in Table 3b can be interpreted. Reporting of ferrofluid formulation remains heterogeneous: particle material, carrier fluid, concentration, viscosity, saturation magnetization, and batch or service age are often incomplete. This limits comparison because magnetization, viscosity, temperature response, and interface stability depend on formulation. Geometry reporting is likewise incomplete for shaft diameter, clearance, pole-tooth number, stage width, and magnetic-source configuration; equal speed or pressure values do not make pressure capacity or lifetime comparable across different structures. Operating conditions must also be interpreted jointly. Rotational speed and linear speed cannot be compared without shaft diameter, while pressure, temperature, medium, cooling boundary, and static versus rotating configuration can change the governing mechanism. Water, gas/vacuum, and other liquid media need not share the same leakage or interface-failure process. Durations reported as hours, rotations, cycles, signal windows, and independent runs are not interchangeable: a large image or window count is not a large number of independent durability tests. A pressure-capacity result defines an operating boundary; leakage onset, loss of watertightness, inability to hold pressure, prescribed state labels, and thermal or operational instability are different failure or state criteria. Temperature, torque, pressure, leakage, and interface visualization may reveal mechanisms, but many studies lack synchronized multisource trajectories, calibration history, raw trajectories, or sensor-uncertainty reporting [17,24,28,32,41,42]. The direct ferrofluid-seal diagnostic studies [30,31] demonstrate bench-scale state recognition only; their device-specific datasets and splits do not establish cross-condition, cross-structure, or field performance. No reviewed primary study provides a directly validated ferrofluid-seal run-to-failure RUL benchmark. Therefore, transferable results in Table 3b identify methodological requirements rather than rank methods. The comparison exposes a reporting and validation gap rather than a universally superior ferrofluid, geometry, sensor, or diagnostic method.

4.4. Physics-Informed and Multisource Fusion Diagnosis

Because the observable responses summarized in Sections 2 and 3 arise from coupled operating conditions, no single signal is expected to represent every degradation state. Multisource fusion can therefore improve robustness by combining complementary measurements, subject to the validation limits discussed in Section 4.3 [30,31,55].

Conceptually, a candidate multisource health representation can be expressed as a constrained weighted combination of condition-normalized, dimensionless single-domain indicators, namely:

$$HI_f(t; c) = \sum_{i=1}^n w_i g_i[HI_i(t); c] \quad (6)$$

where $HI_f(t; c)$ is the fused health indicator at time t under operating-condition vector c . Here, HI_f is the mathematical representation of the candidate HI_{Fusion} used in Tables 1 and 5. $HI_i(t)$ is the i th raw or single-domain candidate health indicator; $g_i[HI_i(t); c]$ is a condition-calibrated normalization mapping; w_i is the fusion weight assigned to the normalized i th indicator; and n is the number of indicators included in the fusion. The condition vector c may include rotational speed, applied differential pressure, ambient temperature, medium temperature, medium type, cooling state, operating phase, and seal structure or configuration. Not every study must include all variables, but c must include those that materially affect the relevant baseline. HI_f is a dimensionless composite representation of condition severity or risk within a defined calibration and operating range. It is not itself a physical pressure, leakage rate, temperature, damage variable, failure probability, or remaining useful life.

If HI_f is to be interpreted as a failure probability, a separate probabilistic calibration against observed outcomes is required. If it is used for RUL prediction, a temporal degradation model and a documented functional-failure threshold are additionally required. If it is used for maintenance triggering, the calibrated threshold must be interpreted together with failure consequence, safety boundaries, and execution authority.

$$w_i \geq 0, i = 1, \dots, n, \text{ and } \sum_{i=1}^n w_i = 1 \quad (7)$$

Weights may be physics-informed or expert-specified when data are limited but the dominant failure mechanism and operating condition are explicit; such weights require stated physical rationale, sensitivity analysis, and must not be called optimal. They may be data-calibrated against diagnostic separation, monotonicity, threshold relevance, prognostic error, likelihood, or calibration objectives using only run-level training and validation data, with constraints or regularization to prevent one channel from arbitrarily dominating. Equal weights may serve as a transparent baseline, but do not imply equal physical contribution or prior calibration and should be compared with justified alternatives. Weight magnitude should not be interpreted directly as physical causality. It represents the contribution assigned to a normalized information channel within the selected fusion model. Before assigning weights, correlation, mutual redundancy, condition dependence, sensor drift, and common-mode disturbance should be examined; highly correlated channels may require removal, reduced joint weight, grouped or hierarchical fusion, or an explicitly reported redundancy treatment.

In the context of ferrofluid seals, HI_i may be derived from one of the mechanism-specific observable domains summarized in Table 2. The expression does not prescribe a validated universal algorithm or a fixed set of weights. It represents a generic candidate fusion structure whose normalization maps, weights, thresholds, valid operating range, and uncertainty must be calibrated and verified for the intended seal and task. Each g_i

output should use a consistent risk-increasing direction and combine only normalized, dimensionless components; raw temperature slope, pressure margin, AE energy, vibration RMS, leakage, and torque deviation must not be added directly. Component contributions $w_i g_i[HI_i(t);c]$ should be retained for traceability so that an increase in HI_f can be attributed to thermal, pressure, leakage, AE, vibration, or torque evidence rather than interpreted as an unexplained single score.

Multisource fusion is not automatically more robust. Signals that are strongly correlated may add redundancy rather than independent evidence, while sensor drift, missing channels, asynchronous sampling, and inconsistent operating-condition coverage can reduce reliability. Feature-level and decision-level fusion can remain more traceable than end-to-end latent fusion, but each fusion weight requires calibration and uncertainty assessment. Sensor combinations should therefore be selected from the relevant failure risk and information complementarity, not from sensor count alone. When one channel is missing or judged unreliable, the remaining weights should not be renormalized automatically unless that reduced-channel configuration has been calibrated and validated; otherwise, the system should report reduced confidence or abstain from a decision.

Physics-informed or hybrid approaches use physical knowledge to constrain feature selection, state estimation, weight allocation, or interpretation of learned outputs. They can be attractive when failure samples are limited or operating conditions drift, but the physical constraint, model discrepancy, and learned component must remain traceable. Transferable studies suggest potential for complex-system estimation [82–86]; for ferrofluid seals, this potential still requires direct held-out-condition and structure validation before it can be treated as an established diagnostic or RUL solution.

Multisource fusion also introduces synchronization, placement, and noise-management challenges because signal sources differ in sampling frequency and sensitivity. The central implementation task is therefore to normalize and combine physically meaningful HIs without creating an uninterpretable black box. Future work should assess adaptive fusion weights, cross-condition consistency, and the connection between a fused state representation and downstream diagnosis, prognosis, and maintenance decisions.

4.5. Main Methods and Implementation Paths for Remaining Useful Life Prediction

For ferrofluid seals, remaining useful life (RUL) prediction aims to estimate the usable time left before functional failure at the current time. If the current time is denoted as t and the time at which the system reaches failure is denoted as t_f , RUL can be defined as:

$$RUL(t) = t_f - t \quad (8)$$

For a degrading system, the failure time t_f is usually not directly observable. Instead, it is determined by the time at which a degradation variable or health indicator reaches a preset failure threshold. If the degradation state or health indicator is denoted as $HI(t)$ and the failure threshold is denoted as HI_{th} , the failure time can be expressed as:

$$t_f = \inf\{t : HI(t) \geq HI_{th}\} \quad (9)$$

The definitions show that RUL prediction requires a degradation representation that reaches a defined failure boundary. For ferrofluid seals, the mechanism-specific candidates for this representation are summarized in Sections 2 and 3; the prognostic task is to estimate threshold-crossing time and its uncertainty from a sufficiently stable HI rather than to extrapolate a raw signal directly.

RUL methods applicable to sealing systems and related degrading equipment can be grouped into three broad categories.

The first category comprises statistical models based on stochastic degradation processes. These methods usually treat the degradation quantity as a process that evolves randomly over time. Typical examples include the Wiener process, the Gamma process, and their extended models. In service-life assessment of hydraulic reciprocating rod seals, leakage amount can be used as a performance-degradation indicator, and measurement errors and stochastic processes can be introduced for service-life prediction [64]. A nonlinear degradation model can also be used to handle multisource uncertainties and obtain the service-life probability distribution [87]. A related piston-rod seal study used acoustic-emission RMS sequences from four run-to-failure tests, fitted the first 15 samples, and forecast the next 10 samples with ARIMA. The reported results were RTF1: RMSE = 0.187 mV and MAPE = 20.26%; RTF2: RMSE = 0.326 mV and MAPE = 28.99%; RTF3: RMSE = 0.053 mV and MAPE = 4.95%; and RTF4: RMSE = 0.104 mV and MAPE = 8.88% [34]. The lower RTF3 and RTF4 errors than RTF1 and RTF2 show marked variation among runs; the original study also found sensitivity to sequence-variance shifts and weak temporal correlation. Four tests are insufficient to demonstrate general applicability, and these results are transferable hydraulic-piston-rod-seal evidence rather than ferrofluid-seal RUL benchmarks. For ferrofluid seals, the method requires a continuously defined degradation quantity, a justified failure threshold, and explicit uncertainty evaluation before a threshold-reaching model can produce a credible life distribution, confidence interval, or risk probability.

The second category uses deep learning and multisensor fusion. A transferable TCN-BiGRU model improved RUL prediction on a different equipment dataset [71]. Its reported performance is not directly comparable with the seal-specific studies in Table 3. Under limited sensing, virtual-sensor methods can reconstruct latent degradation states and estimate RUL or state-of-health probabilities [86]. For ferrofluid seals, such models could integrate acoustic-emission, temperature, pressure, and vibration time series. Credible accuracy claims require run-to-failure data, defined prediction horizons, held-out tests, error metrics, and uncertainty coverage. Without consistent thresholds and data-collection protocols, good local fit does not demonstrate engineering transferability.

The third category comprises physics-informed and hybrid RUL methods. Transferable studies suggest that combining mechanistic degradation priors with data-driven models can improve robustness under limited data and condition drift [82,84,85]. Mechanistic models can constrain pressure attenuation, heat accumulation, or interfacial stability, while learning models capture nonlinear evolution and unit-to-unit variation [82]. System knowledge can also guide health-state recognition before diagnostic outputs enter the prognostic model [84]. Other work links health-indicator construction, degradation-state recognition, and life estimation under limited data [88]. This pathway is relevant to ferrofluid seals because failure datasets are scarce and degradation depends on speed, pressure, medium, and temperature. Purely black-box learning is unlikely to meet reliability requirements without direct validation and physical constraints.

A quantitative comparison also reveals why ferrofluid-seal RUL should not yet be evaluated by a single headline metric. The directly relevant studies [30,31] report diagnostic classification rather than run-to-failure prognosis. The transferable ARIMA example [34] reports forecasting error from four piston-rod seal tests, whereas the mechanical-seal study [55] demonstrates an incipient-fault detection framework, but its reported lead-time unit is internally inconsistent with the sampling interval. It should therefore be treated as qualitative early-warning evidence rather than as a validated quantitative RUL benchmark. Future ferrofluid-seal studies should report the number of run-to-failure trajectories, split at the trajectory or rig level rather than at adjacent time windows, operating-condition coverage, failure-threshold definition, prediction horizon, MAE/RMSE/MAPE, uncertainty

calibration or coverage, false-alarm burden, and inference latency. Statistical degradation models remain attractive when degradation thresholds are transparent and data are limited; deep models may be useful for high-dimensional signals when sufficient independent trajectories are available; and hybrid models are promising for ferrofluid seals because they can incorporate pressure, thermal, and interface physics, although their advantages still require direct cross-condition and run-to-failure validation.

These RUL pathways differ principally in their requirements for health-indicator stability, run-to-failure data, physical priors, uncertainty output, and online implementation. Their broader engineering trade-offs are compared in Table 4.

Table 4. Critical comparison of diagnosis and prognosis method families relevant to ferrofluid seals.

Method	Data and Model	Traceability	Condition Transfer	Uncertainty	Online Use	Engineering Role	Evidence Limits
Mechanistic and model-driven	Physics; geometry; fluid, thermal, and boundary data; calibration	High; finds weak regions and root causes	Transfers if physics holds; recalibrate for materials, gaps, or boundaries; aging and assembly effects remain hard	Parameter and model errors can be propagated; formal studies are rare	FE models are offline; reduced models support online use	Cause tracing; operating limits; design feedback	Direct: substantial ferrofluid-seal mechanism and performance evidence. Proposed/limited: online residual diagnosis and real-time reduced-order implementation. Direct: limited bench-scale ferrofluid-seal state recognition [30,31]. Unvalidated: cross-rig and field diagnosis.
Classical data-driven	Labeled data; hand features; state and condition labels	Moderate; feature meaning needs physical mapping	Weak beyond seen conditions; needs normalization or condition inputs	Point outputs often lack calibrated uncertainty	Low after training; needs stable sensing and features	State classes; early warning; bench diagnosis	Direct: small within-dataset ferrofluid-seal image-classification evidence [30]. Transferable/proposed: sequence learning, cross-condition deployment, and RUL.
Deep learning and sequence learning	Many labeled images or time series; independent run-to-failure data	Low; saliency does not prove causality	Can learn nonlinear effects; needs adaptation or condition inputs	Bayesian, ensemble, or conformal methods are needed	High training load; online use needs latency, memory, and sync tests	Signal or image classes; nonlinear sequences; RUL needs trajectories and thresholds	Transferable: seal and mechanical-system degradation/RUL studies. Proposed for ferrofluid seals; no direct run-to-failure validation. Mainly transferable or conceptual for ferrofluid seals; direct quantitative diagnostic or RUL validation remains absent or very limited.
Stochastic degradation	Monotonic HI; repeated trajectories; thresholds; process model	High for HI paths and thresholds; weak for raw signals	Covariates help; fixed process models may fail as mechanisms change	Probabilistic RUL and intervals when model assumptions hold	Low to moderate; supports online updates	Degradation; threshold crossing; RUL; maintenance risk	
Physics-informed hybrid	Data plus physical priors, model knowledge, and calibration	Moderate to high if physical and learned parts are traceable	Potentially stronger transfer; needs held-out-condition and structure tests	Separate parameter, model, and data uncertainty	Moderate to high; online use needs reduced models	Small-sample diagnosis; condition states; constrained RUL; design support	

Table 4. Cont.

Method	Data and Model	Traceability	Condition Transfer	Uncertainty	Online Use	Engineering Role	Evidence Limits
Multisource fusion strategy	Synced calibrated sensors; condition labels; drift and missing-data handling	Depends on fusion level; feature and decision fusion are more traceable	Signals can help; correlation, drift, missing data, and asynchrony hurt	Propagate sensor and fusion uncertainty; rare in studies	Extra sensors, sync, bandwidth, and compute	Complex states; early warning; robust diagnosis; RUL inputs	Limited direct evidence: AE-based state recognition with pressure-assisted labeling [31], rather than validated multisensor input fusion. Proposed/transferable: fused HIs, broader sensor fusion, missing-channel handling, and RUL integration.

Note: The comparisons are qualitative, evidence-informed assessments rather than universally validated rankings. Data demand, robustness, computational burden, and online suitability depend on model scale, sensor configuration, operating-condition coverage, and implementation hardware. AE = acoustic emission; FE = finite element; HI = health indicator; RUL = remaining useful life.

The method families compared below are not completely mutually exclusive. Mechanism-based, classical data-driven, deep-learning, stochastic-degradation, and physics-informed approaches primarily describe inference or modeling paradigms. Multisource fusion is instead an information-integration strategy that can be combined with several of these paradigms. Table 4 therefore compares their dominant engineering characteristics and intended roles rather than treating them as strictly exclusive algorithm classes. The comparison is grounded in the direct ferrofluid-seal evidence in Table 3 and the transferable diagnostic, prognostic, and hybrid-method evidence reviewed in this section [30,31,33,34,55,74–76,82–90].

Method selection should begin with the engineering task rather than an assumed universally preferred algorithm. When the need is to explain a physical cause, locate a weak region, assess an operating envelope, or provide design feedback, mechanism-based models are the primary choice, provided that parameters and boundary conditions can be calibrated. When the task is rapid recognition of a bounded set of well-labeled states using a stable sensing pipeline, classical feature-based learning can be efficient. Deep and sequence models become appropriate only when sufficiently independent images or run-to-failure trajectories cover the relevant operating conditions, and latency, hardware, and generalization are validated. Stochastic degradation models are preferable when a monotonic HI, a justified threshold, and repeated trajectories support probabilistic threshold-crossing RUL estimation. Physics-informed or hybrid models are promising when data are limited and physical priors are available, but their claimed robustness still requires held-out-condition and structure tests. Multisource fusion should be introduced only when signal complementarity exceeds synchronization, sensor-health, and reliability costs; it supplies an information representation rather than automatically constituting a complete RUL model. Current ferrofluid-seal research most urgently needs direct run-to-failure datasets with condition labels, external-rig validation, uncertainty calibration, and online deployment metrics such as inference latency, memory demand, and synchronization overhead. No method is universally optimal across all tasks, evidence levels, and operating constraints.

5. Maintenance Decision-Making and Closed-Loop Health Management

5.1. Logic and Implementation Pathways for Maintenance Decision-Making

For ferrofluid seals, monitoring, diagnosis, and remaining useful life prediction are valuable only when they lead to a maintenance decision or an operational intervention. A complete prediction-and-health-management system therefore includes state awareness, diagnosis and prognosis, and maintenance execution [69,72,91]. State awareness provides measurements, diagnostic inference separates normal and degraded states, and prognosis estimates future risk. Those outputs must be connected to a feasible action, appropriate authority, and a check of the outcome. Decision rules also require an explicit connection to the available sensor evidence and operating constraints so that an alarm cannot be translated into an action that the system cannot safely execute. The purpose of this section is to specify what is done after an abnormal state or an approaching threshold has been identified.

The maintenance evidence should also be interpreted by maturity level. Direct ferrofluid-seal studies support the physical relevance of cooling, operating-condition limitation, start-up adjustment, ferrofluid renewal, and replenishment under particular structures and test conditions. Related seal, valve, flow-control, and rotor studies provide transferable evidence for other intervention mechanisms. However, the complete mapping from a calibrated HI through diagnosis or RUL to an automatically executed and verified action is a proposed ferrofluid-seal health-management pathway rather than a directly validated end-to-end system.

Condition-based maintenance and active control are related but distinct functions. Condition-based maintenance is the decision layer that selects the timing and type of inspection, operating restriction, replenishment, repair, replacement, or shutdown according to current and predicted health. Its execution may be manual, supervisory, or automated. Active control is the online execution of a controllable operating action through feedback, a control rule, an actuator, and safety constraints. Therefore, a maintenance decision does not necessarily constitute active control, and an active-control action should be initiated only after its monitored, diagnostic, or prognostic trigger, operating authority, and safety boundary have been defined.

Maintenance decisions should follow the evidence chain established in Sections 2–4: observed state changes are interpreted through health indicators, then translated into actions. The implementation path has four levels: multisource state awareness, diagnostic and prognostic assessment, condition-based maintenance decision and execution, and design feedback. The required action may be a temporary operating restriction, inspection, replenishment, or planned maintenance, depending on risk class, resource constraints, safety requirements, and operating authority. When risk is uncertain, the selected intervention should be reversible and followed by short-interval reassessment. Operating actions can include speed or pressure-difference adjustment, ferrofluid replenishment, cooling, vibration control, or alignment correction; only feedback-driven automatic execution through a defined control rule, actuator, and safety constraints constitutes active control. Accumulated results can then inform structural, magnetic-circuit, material, and sensing revisions [70,86,88,92].

Engineering implementation includes condition-based maintenance, online operating intervention, and offline optimization. Condition-based maintenance may be executed manually, under supervisory authority, or through an approved automated workflow. Online intervention adjusts boundary conditions or issues threshold-based warnings without immediate component replacement; it qualifies as active control only when a feedback loop, defined control rule, actuator, and safety constraints govern the execution. Offline optimization uses long-term monitoring and failure experience to revise the structure, medium,

or material strategy [92,93]. Online decisions should specify the trigger, action, duration, authority, and reassessment point, while offline decisions should retain an auditable link between recurrent state evidence and the design changes that are justified. Escalation from warning to restriction or shutdown should be based on documented thresholds and the consequence of failure. Together, these distinct functions turn diagnostic and prognostic information into a practical maintenance loop.

Figure 4 presents this proposed health-management framework: monitoring and health assessment provide evidence, diagnosis identifies the current abnormal state and likely source, prognosis estimates the available operating time, and condition-based maintenance selects the immediate response. The observed outcome can then feed back to subsequent operating and design decisions [69,72,88,91,92]. The framework therefore emphasizes a pathway from state assessment to intervention and feedback rather than a fully validated autonomous-control implementation.

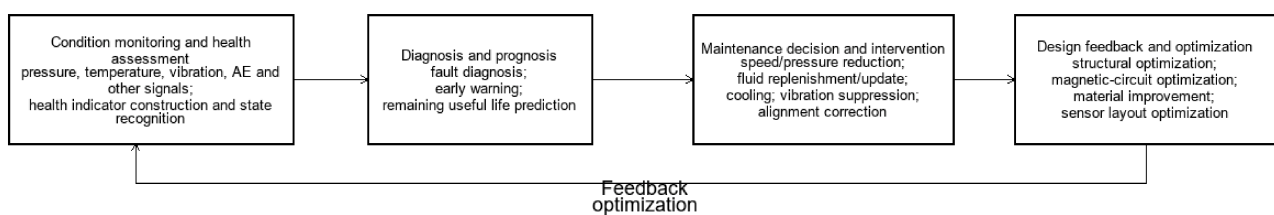


Figure 4. Engineering closed-loop health-management framework linking state assessment, intervention, and design feedback for ferrofluid seals.

5.2. Maintenance Trigger Mechanisms Based on Health Indicators

The candidate health indicators introduced in Section 3.6 and mapped to degradation mechanisms in Table 1 provide the inputs to the indicator-risk-action relationships summarized in Table 5.

Maintenance decisions require health indicators to be converted into executable trigger conditions. A practical trigger defines the indicator anomaly, its risk meaning, the recommended action, and the relevant operating boundary. Warning, restriction, and failure regions can then be linked to escalating actions using performance range, life assessment, and environmental conditions [69,72,91,94–96].

A sustained increase in temperature-rise slope or steady-state temperature difference indicates thermal risk and should trigger cooling, speed reduction, or inspection of the thermal path. High-speed experiments and thermo-mechanical studies support the relevance of heat dissipation, cooling structure, and ferrofluid thermal conductivity to operating stability [42,43,50].

A declining pressure margin, accelerating pressure decay, or deviation from the pressure baseline indicates increased risk of loss of sealing capability. Recommended actions are pressure-difference limitation, speed-limited operation, and inspection of the magnetic-circuit or operating boundary. The physical basis is the available magnetization-pressure margin, whose dependence on high-speed operation and structural parameters has been demonstrated experimentally and analytically [1,29,62].

For liquid-medium conditions, rising leakage, loss of watertightness, or a life indicator near its threshold should trigger ferrofluid replenishment or renewal, medium review, and contamination control. These actions address the increased risk of interface-related liquid loss; water-environment experiments, leakage analyses, and replenishment studies provide the relevant evidence [23–25,95,97].

A change from stable to abnormal acoustic-emission behavior, or a sharp change in acoustic-emission energy or features, should trigger early warning, gradual operating-

condition adjustment, and intensified local monitoring. This response uses AE as an early indication of a developing state transition and does not wait for macroscopic pressure loss or leakage confirmation [30,31,56].

Deteriorating vibration RMS, kurtosis, or envelope characteristics should trigger alignment correction, vibration suppression, or avoidance of resonance conditions. The short physical basis is that clearance variation and dynamic loading can reduce operational stability; ferrofluid and related sealing studies support the relevance of eccentricity, vibration adaptation, and resonance-related leakage risk [26,44,45,66].

Maintenance triggering is therefore an indicator-risk-action mapping rather than a single alarm value. Multisource HIs, risk classification, and actuator capability should be considered together so that the trigger remains both forward-looking and implementable [86,88,92].

Table 5 summarizes the correspondence between health-indicator anomalies, maintenance actions, expected effects, and design-feedback directions.

Any HI or HI_Fusion threshold used for maintenance triggering must be calibrated against a documented functional or risk criterion. The weighting and threshold values are not specified by this review and should not be transferred directly among different seal structures or operating conditions.

Table 5. Evidence-informed candidate maintenance actions associated with health indicators and design-feedback directions.

Health Indicators/Abnormal Characteristics	Main Reflected Problems	Typical Maintenance Actions	Expected Effect	Design Feedback Direction
Increasing HI_T_slope and steady-state temperature difference	Enhanced heat accumulation and loss of thermal balance, with potential viscosity and magnetization drift	Enhance cooling, reduce rotational speed, and optimize operating conditions	Limit temperature rise and delay thermally dominated degradation	Optimize heat-transfer pathways, housing heat dissipation, and thermomechanical reliability
Declining HI_P_margin and increasing pressure-decay rate	Weakening of the magnetization-pressure barrier and reduced pressure capacity	Limit differential pressure or speed; inspect the magnetic-circuit and centrifugal-instability risk	Prevent local barrier breakdown and delay leakage	Optimize pole-tooth geometry, magnetic-circuit distribution, and centrifugal-load tolerance
Rising HI_Leak or life approaching its threshold	Increasing interfacial instability and risk of watertightness loss under liquid-medium conditions	Replenish or renew ferrofluid; review the medium; control contamination	Extend service life and slow degradation under liquid contact	Optimize stage width, ferrofluid volume, and medium compatibility
Abrupt HI_AE change or increasing abnormal AE energy	Interfacial instability, local friction, or incipient microleakage	Issue an early warning, adjust operating conditions gradually, and intensify local monitoring	Identify incipient anomalies before they develop into macroscopic failure	Optimize AE sensor placement and observability
Increasing HI_Vib or abnormal vibration RMS/kurtosis	Greater risk of eccentricity, disturbance, local weak regions, or contact	Correct alignment, suppress vibration, and avoid resonance	Reduce dynamic amplification of local weak regions	Optimize eccentricity-tolerant structures and gap design
Increasing HI_Torque deviation, abnormal torque fluctuations, or unstable start-up	Increased viscous dissipation, altered flow resistance, or reduced start-up stability	Adjust the start-up method and operating conditions; inspect for local obstruction	Improve start-up stability and reduce energy loss	Optimize shaft-system matching, start-up strategy, and local flow paths

Table 5. *Cont.*

Health Indicators/Abnormal Characteristics	Main Reflected Problems	Typical Maintenance Actions	Expected Effect	Design Feedback Direction
Abnormal multisource indicator HI_Fusion	Coupled degradation that cannot be interpreted reliably from one signal	Use integrated early warning, hierarchical maintenance, and coordinated intervention	Improve maintenance-decision reliability under complex operating conditions	Develop multisensor design and closed-loop health-management architecture

Note: This table is a proposed indicator-risk-action mapping synthesized from direct ferrofluid-seal mechanism or intervention evidence and transferable maintenance evidence. Individual actions such as cooling, ferrofluid replenishment, operating-condition adjustment, or alignment may have supporting experimental evidence, but the complete HI thresholds, automatic trigger rules, combined actions, and closed-loop design-feedback pathway have not been directly validated as a unified ferrofluid-seal system.

5.3. Online Intervention Strategies for Operating Conditions

The operating interventions discussed in this section constitute active control only when they are implemented automatically through feedback, a defined control rule, an actuator, and safety constraints. Supervisory or human-authorized adjustments remain online interventions or condition-based maintenance actions unless the authorization only enables a feedback controller that subsequently governs the final actuation automatically; in that case, the execution layer is classified as active control. When the same actions are applied manually or according to a maintenance schedule, they remain condition-based maintenance or operating procedures. Online intervention at the operational level is an implementation pathway within ferrofluid-seal health management. Its goal is to slow degradation by adjusting boundary conditions such as rotational speed, differential pressure, cooling, start-up method, and disturbance level without immediately replacing the structure or materials. For multiphysics systems such as ferrofluid seals, an intervention is not simply load reduction but a targeted adjustment of operating variables according to the current health state and risk level, with the aim of extending operating time within an acceptable performance range [69,72,92].

For coupled centrifugal and thermal degradation, the principal online interventions are limiting speed or differential pressure and enhancing cooling. If HI_T_slope rises persistently, HI_P_margin declines, or local temperature becomes abnormal, load reduction can reduce centrifugal pressure and viscous dissipation [29,42]. Cooling-structure optimization also reduces local peak temperature and improves thermomechanical reliability [43]. Increasing ferrofluid thermal conductivity can further limit temperature rise and improve high-speed stability [50]. Coordinated load reduction and cooling are therefore evidence-informed interventions for coupled high-speed and thermal degradation. Their physical basis is supported directly, but HI-triggered coordination still requires closed-loop validation.

Under liquid-medium conditions, online intervention focuses on gradual operating adjustments, flow management, and controlled ferrofluid replenishment. Replenishment systems can extend seal life by replacing degraded ferrofluid during dynamic liquid contact [25]. Transferable studies show that active flow-field modification can reduce leakage near a leakage path [98]. Seal-chamber geometry and pressure imbalance also affect leakage and stability [99]. Intervention should therefore extend beyond remediation after leakage and include controlled replenishment and differential-pressure or flow management. Replenishment has direct seal-specific support [25], whereas broader flow-control concepts remain transferable. Their integration into an HI-triggered automatic system requires validation.

For eccentricity, vibration, and start-up instability, interventions should emphasize alignment, resonance avoidance, and controlled start-up. Ferrofluid-seal tests found distinct torque and speed fluctuations under different start-up modes [32]. Variable-torque start-up reduced fluctuations and improved stability. Transferable sealing studies associate resonance with greater leakage risk and amplification of local anomalies [45,66]. Related rotating-system studies show that sealing conditions, working medium, and gap geometry affect damping and unbalanced responses [67,68]. Slow start-up, alignment correction, vibration limits, and resonance avoidance may therefore enlarge the stable operating envelope. Start-up adjustment has direct ferrofluid-seal support, but automatic alignment and vibration-control loops remain unvalidated.

Effective online intervention depends on mechanism-matched coordination rather than any single action. Speed reduction, pressure limitation, cooling, replenishment, controlled start-up, vibration suppression, and centering should be selected according to current HIs. Such coordination connects state assessment to operational intervention while preserving explicit safety and operating boundaries.

5.4. Maintenance Measures for Media and Ferrofluids

Ferrofluid maintenance under liquid or otherwise demanding media should be matched to the most plausible degradation state, rather than treated as a single replenishment task. The maintenance object includes fluid inventory, colloidal and chemical condition, medium exposure, contamination history, and the compatibility of the sealing fluid with the adjacent medium and supporting materials. Direct water-environment studies show that interface evolution and fluid loss can govern the durability of a particular seal [24,25]. These observations do not establish that every later pressure, temperature, torque, or leakage change is caused by material degradation, so maintenance decisions should combine operating history with fluid verification where material changes are suspected.

Replenishment and renewal should not be treated as equivalent actions. Replenishment restores inventory when the retained fluid remains compatible and sufficiently stable. Partial or complete renewal is more appropriate when oxidation, surfactant deterioration, irreversible aggregation, or contamination has altered the retained fluid. The pressurized-water replenishment study [25] supports the value of controlled inventory renewal in its tested device, but it does not show that adding new fluid restores surfactant integrity, redisperses irreversibly aggregated particles, removes contamination, or reverses carrier-fluid oxidation. Sampling, exposure history, and the degree of fluid-property drift should therefore determine whether replenishment, partial renewal, complete replacement, filtration, or medium isolation is justified.

Compatibility screening should be treated as application-specific qualification. It should consider controlled fluid-medium exposure, temperature aging, repeated start-stop or thermal cycling, storage stability, mass or volume change, viscosity and magnetization before and after exposure, visual or particle-stability assessment, interface or wettability response, secondary-material swelling, corrosion, softening, or extraction, and post-exposure leakage or pressure-capacity verification. In [46], kerosene-, engine-oil-, and PAO-based magnetic fluids were screened against ethylene glycol for 60 days; the selected PAO-based formulation was then tested continuously for 96 h over -20 to 80 °C, at a maximum linear velocity of 0.1 m/s and a chamber pressure above 120 kPa, without reported leakage. This result qualifies that prepared formulation and tested device under the stated conditions; it cannot guarantee compatibility across all PAO, glycol, water, or other process-fluid systems.

Carrier-liquid type, particle concentration, surfactant system, and particle-size distribution can affect pressure capacity, torque, viscosity, and medium interaction in a particular

seal [35,100]. Any change in carrier fluid, surfactant system, particle concentration, or formulation should be treated as a requalification rather than routine maintenance, because it may alter magnetic pressure, viscosity, torque, medium compatibility, and the validated operating envelope. Study [47] directly compares pressure-resistance behavior across carrier types, particle concentrations, and capillary gaps, but does not provide long-duration material-aging qualification. Study [48] supplies a large-gap marine design and static pressure/leakage context rather than direct chemical-corrosion validation. These studies should therefore be used as context-specific design inputs, not as a basis for on-site mixing of unvalidated fluids.

Contamination control includes more than removing solid debris. Water or cooling-fluid ingress, sealed-medium intrusion, dust, metallic wear debris, corrosion products, incompatible lubricants, and maintenance-introduced material can change viscosity, dispersion, wettability, interfacial tension, corrosion behavior, or local flow resistance. The source, amount, and duration of exposure should be recorded. Filtration or contamination removal is appropriate only when it does not introduce further formulation imbalance or damage the dispersion; otherwise, partial or complete renewal and medium isolation may be required. The maintenance pathway is therefore inventory verification, sampling and characterization, contamination control, compatibility assessment, and only then an appropriately bounded replenishment or renewal action.

Overall, media and ferrofluid maintenance should connect observed functional changes to a documented material and exposure history. It should not infer a single chemical or colloidal mechanism from leakage alone, nor assume that any replenishment action restores all material properties. This mechanism-matched approach keeps fluid inventory, compatibility, contamination, and formulation stability within the health-management framework while preserving the need for direct material-state verification.

5.5. Design Feedback for Structure, Magnetic Circuit, and Materials

Maintenance records are an important source of evidence for design optimization. Persistent temperature rise, declining pressure margin, short liquid-medium life, worsening vibration, and recurrent local anomalies should inform subsequent design revisions [69,72,93].

Thermal design feedback should target housing thermomechanical reliability and heat-transfer pathways. A persistently high temperature-rise rate at a given speed may indicate inadequate heat dissipation, heat-sensitive materials, or poor gap thermal coupling. Cooling-structure optimization can reduce local peak temperature and improve structural reliability [43]. Increased ferrofluid thermal conductivity can also reduce high-speed temperature rise and improve stability [50]. Thermal anomalies should therefore motivate changes to heat-dissipation structures, material properties, and local thermal pathways, not only stronger operational cooling.

Declining pressure capacity should prompt reassessment of the magnetic circuit and pole-tooth geometry. A persistent loss of pressure margin may indicate insufficient robustness to centrifugal loading or local pressure fluctuations. Centrifugal effects reduce seal pressure capacity [29]. Sandwich circuits, helical teeth, and specialized valve circuits show that topology, tooth geometry, and excitation alter magnetic flux and baseline pressure capacity [58,61,62]. Radial-electromagnet designs can improve pressure performance under large gaps and runout [101]. Switchable shaft wettability may also increase pressure tolerance [102]. Pressure anomalies may therefore reveal design weaknesses in the magnetic circuit, tooth profile, gap, or interface.

Design feedback for liquid-medium durability should address stage width, ferrofluid volume, medium compatibility, and self-healing. Water studies show that formulation, stage width, and fluid volume affect long-term stability and leakage [24]. Ethylene-glycol

studies likewise emphasize compatibility and erosion resistance [46]. Recurrent premature failure may therefore reflect an unsuitable stage geometry, fluid inventory, or medium-adaptation strategy rather than inadequate maintenance. Self-healing studies show that clearance, tooth number, height, and position influence recovery in several seal structures [103,104]. Large-diameter eccentric-shaft studies also link stability to ferrofluid properties, clearance, tooth width, and saturation magnetization [105]. Service records should guide redesign of the interstage layout, fluid inventory, and material parameters for long-term operation.

Eccentricity, vibration, and environmental anomalies should inform improvements in structural robustness and environmental tolerance. Large-gap ferrofluid seals can improve stability in vibration environments [44]. If monitoring identifies recurrent vibration- or alignment-induced anomalies, redesign should address robust gaps, vibration resistance, self-healing, and contamination protection. The design objective should expand from static performance to combined observability, robustness, and maintainability.

Design feedback converts evidence accumulated through monitoring, diagnosis, prognosis, and maintenance into actionable engineering knowledge. The priority is not simply to add optimization variables. It is to map thermal anomalies, pressure loss, shortened life, and local instability to structural, magnetic-circuit, and material modifications. This mapping can move design from experience-based iteration toward health-information-informed optimization. The complete end-to-end pathway remains proposed and has not yet been validated for ferrofluid seals.

Figure 4 serves a different role from Figure 1. Whereas Figure 1 organizes the review-level evidence chain, Figure 4 translates that chain into an engineering closed-loop health-management framework. It shows how monitored states and prognostic results can trigger maintenance or operational interventions and how the observed outcomes can feed back into subsequent operating and design decisions. The intervention block may therefore represent a manually executed condition-based maintenance action, a supervisory operating adjustment, or an automatic active-control action. The figure does not imply that all maintenance decisions are executed automatically. Accordingly, Figure 4 is an author-synthesized proposed framework. Its individual sensing, diagnostic, maintenance, or intervention components have different evidence levels, and the complete end-to-end loop has not been directly validated for ferrofluid seals.

6. Challenges and Actionable Future Research Directions

The next stage of ferrofluid-seal reliability research requires more than additional algorithms or isolated performance tests. Four gaps remain central: benchmark degradation data, physically consistent health indicators, trustworthy diagnosis and prognosis, and verification of condition-based intervention and feedback-driven active control [69–72,88,91–93,106]. Each research direction should be associated with a defined data requirement, validation protocol, reporting output, and engineering verification milestone. The roadmap below therefore translates the current evidence gaps into recommended minimum requirements for benchmark data, cross-condition validation, uncertainty-aware prognosis, intervention experiments, and field-oriented verification. These are evidence-informed research recommendations, not an established universal standard. All benchmark requirements, uncertainty-aware RUL protocols, cross-condition validation levels, and closed-loop verification milestones in this section are proposed future research directions. They should not be interpreted as methods already validated for ferrofluid seals.

6.1. Benchmark Degradation Datasets and Reporting Requirements

A benchmark degradation dataset should pair each monitoring record with sufficient seal, fluid, and acquisition context. Recommended structural metadata include seal configuration, shaft diameter, radial and axial clearance, pole-tooth number and geometry, magnetic-source arrangement, and a magnetic-flux or pressure-capacity baseline. Fluid metadata should include carrier liquid, particle concentration, viscosity, saturation magnetization, batch, service age, and sealed medium. The dataset should also identify sensor type and location, acquisition hardware, calibration, rotational speed, differential pressure, ambient and medium temperature, duration, start–stop events, runout or vibration condition, cooling condition, and all maintenance or intervention events. Signals without these structure, fluid, and sensor-location records cannot support reproducible comparison. For long-duration material-degradation studies, recommended records additionally include initial and sampled fluid properties; sampling time; replenishment and replacement quantity; fluid mass or volume history; viscosity; magnetization or saturation magnetization; particle/agglomeration or sedimentation records where available; water or contamination records where relevant; and material-compatibility exposure history. These records need not be available for every dataset, but their absence should be explicit.

A minimum core record should include synchronized timestamps and operating history, rotational speed, applied differential pressure, upstream/downstream or differential-pressure measurements, temperature, and leakage or another explicitly defined functional-performance record. When leakage cannot be measured continuously, the collection method and functional-failure criterion should be documented. Torque should be added for viscous-dissipation and start-up studies, vibration or shaft-runout measurements for eccentricity/disturbance studies, and acoustic emission for interface-transition and microleakage studies. Each release should report the sampling frequency, synchronization accuracy, missing-data status, sensor drift, and recalibration history for every available channel. Labels should identify normal operation, detectable degradation onset, warning state, functional failure, shutdown or maintenance point, leakage or pressure-loss criterion, intervention time, and post-intervention state. Complete run-to-failure or controlled-degradation trajectories, run identifiers, repeated comparable tests, multiple conditions, censored runs, and intervention and non-intervention trajectories are required where applicable. Adjacent windows from one continuous run must not be counted as independent samples.

Public releases should provide a data dictionary, units and sensor definitions, preprocessing and exclusion history, failure-event definitions, dataset version, license, citation information, and recommended baseline tasks. Splits should be predefined at the run level: training, validation, within-condition test, held-out-condition test, and, when available, external-rig or external-structure test. Three complementary benchmarks are recommended: state recognition across normal, degraded, warning, and failure states; cross-condition diagnosis on unseen speed, pressure, temperature, medium, or structure; and RUL prediction from independent trajectories to a stated functional-failure threshold. Their split rules, metrics, and failure criteria differ; high classification accuracy does not replace RUL validation [23–29,106–108].

6.2. Physically Consistent Health-Indicator Validation

Health indicators should be selected as measurable representations of a specified degradation path and functional threshold, rather than only as discriminative features on one dataset. Candidate indicators, including HI_T_slope, HI_P_margin, HI_Leak, HI_AE, HI_Vib, HI_Torque, and HI_Fusion, should be evaluated with the same logic: sensitivity to the target degradation process, monotonicity or trend consistency where RUL is intended, robustness to normal speed, pressure, or temperature variation, explicit cross-condition

baseline normalization, repeatability across runs, threshold relevance to pressure capability, leakage, or loss of sealing function, and measurement and between-run uncertainty. Strong classification alone does not demonstrate physical consistency [30,31,70,86].

Each HI study should report its physical interpretation, sensor channel and placement, condition-specific baseline, normalization method, failure criterion, repeated-run variation, and performance under at least one held-out condition. Correlation coefficients or a single within-dataset accuracy should not be the sole selection criterion. Local interface observability remains important because many macroscopic signals reveal outcomes after leakage or instability has developed; measurements that link evolving interface, thermal, or rheological states to a functional threshold are needed for earlier warning [109–114].

Material-degradation labels should not be assigned from pressure, temperature, torque, or leakage alone. Where carrier loss, aggregation, oxidation, contamination, or incompatibility is claimed, the label should be supported by fluid inventory, exposure history, offline material-property measurement, or another justified reference test.

The immediate research milestone is therefore a calibrated HI set whose trends can be reproduced across comparable runs and whose warning thresholds are traceable to an engineering consequence. Such a set can then support diagnosis, RUL prediction, and intervention triggering without treating raw signal variation as a health state by default.

6.3. Cross-Condition Validation and Uncertainty-Aware Prognosis

Validation should proceed through four distinct levels. Level 1 is within-condition validation using independent runs and run-level splits. Level 2 is held-out-condition validation, retaining an unseen speed, differential pressure, medium temperature, cooling condition, or eccentricity or vibration level for testing; leave-one-condition-out and train-on-low / test-on-high designs are useful examples. Level 3 is cross-structure validation across shaft diameter, clearance, pole-tooth configuration, magnetic circuit, or ferrofluid formulation. Level 4 is external-rig validation using an independent test platform, and ideally an independent team or sensing system. Random window splits are not cross-condition validation. Diagnosis studies should report class distribution, split unit, accuracy, class-wise precision, recall, F1 score, confusion matrix, false-alarm and missed-detection rates, within-condition and held-out-condition performance, inference latency, computational demand, repeated-run confidence intervals, and the cross-condition performance drop [30,31,55,82,84–86,106–108].

RUL studies should define the number of independent run-to-failure trajectories, prediction origin and horizon, functional-failure threshold, censoring, and operating-condition coverage. Point forecasts should report MAE, RMSE, MAPE or another justified relative error, together with early and late prediction bias. Probabilistic forecasts should also report prediction-interval coverage, interval width or sharpness, a calibration curve, and, when appropriate, a score such as the continuous ranked probability score or negative log-likelihood. A probability output is not automatically calibrated, and a wide interval is not automatically useful. Engineering outputs should include the probability of failure within a stated horizon, false-maintenance and missed-failure risk, and uncertainty across life fractions. Measurement, condition, model, and degradation-path uncertainty should be distinguished whenever the data support that separation [34,63–65,70,87,88].

Progression beyond a laboratory method claim requires consistent held-out-condition performance, transparent uncertainty calibration, and evidence that the output remains useful for a defined maintenance decision. These requirements are intended to make transferability and risk visible, rather than to impose a single optimal protocol.

6.4. Experimental Verification of Closed-Loop Interventions

Closed-loop studies should use a detect-decide-act-verify protocol. Detect identifies risk from an HI, a diagnostic result, or an RUL estimate; decide selects an action according to a predefined trigger condition and safety boundary; act applies cooling, ferrofluid replenishment, speed or differential-pressure limiting, gradual operating-condition adjustment, vibration suppression, or alignment correction; and verify compares the post-action state with the pre-action trajectory. Each intervention experiment should include a baseline or no-intervention group, a triggered-intervention group, repeated runs under comparable initial conditions, trigger definition, action magnitude and duration, actuation latency, observation window, and termination and safety criteria. Delayed, fixed-schedule, or alternative-action controls may be added when feasible [69,72,91–93].

In this proposed protocol, the act step may be manual, supervisory, or automatic; only the feedback-driven automatic implementation is classified as active control.

Cooling experiments should evaluate HI_T_slope, maximum and steady-state temperature, pressure margin, torque, energy demand, response latency, post-action rebound, and whether leakage or degradation rate decreases. Ferrofluid replenishment experiments should report quantity and rate, leakage, pressure capability, service-life change, fluid loss, contamination risk, medium compatibility, and secondary effects of excessive replenishment. Speed or differential-pressure adjustment should report action time and magnitude, HI_P_margin recovery, leakage, temperature, torque, production or performance loss, and recurrence after restoration. Vibration, alignment, or start-up actions should report HI_Vib, runout or alignment, torque fluctuation, pressure response, resonance avoidance, and repeatability of improvement [23–25,42–45,50].

An intervention should not be judged successful because one signal briefly decreases. Verification should assess immediate risk response, functional recovery of pressure capability, leakage, or stability, durability during a stated observation window, repeatability across runs, side effects such as energy demand, torque, or contamination, life benefit or delayed functional failure, and decision reliability through false triggers, missed triggers, and unnecessary maintenance. Continuous pre-, during-, and post-intervention records are needed to establish these outcomes.

The engineering milestone is a repeatable bench demonstration in which a stated trigger produces a safe action, a measurable functional benefit, and no unacceptable side effect. Special-environment applications should then be evaluated under their relevant medium, temperature, pressure, and disturbance boundaries before field-oriented claims are made [22,44,46,105,115–118].

6.5. Staged Research Roadmap and Verification Milestones

An evidence-informed progression is proposed in five stages. Stage I, reproducible data and HI calibration, establishes the data dictionary, run-level splits, sensor and HI baselines, and functional-failure criteria. Stage II, cross-condition and external validation, tests unseen speed, pressure, temperature, and medium conditions and then cross-structure or cross-rig transfer, reporting the performance drop. Stage III, uncertainty-aware diagnosis and RUL, produces confidence or RUL distributions, checks calibration, and relates prediction to maintenance risk. Stage IV, closed-loop bench demonstration, executes detect-decide-act-verify experiments for cooling, replenishment, limiting, or operating adjustment and verifies benefit, durability, and repeatability. Stage V, engineering pilot and specification development, examines long-duration or field-oriented operation, sensor drift, missing data, maintenance cost, intervention authority, and reproducible test and reporting specifications. Evidence from each stage should support the next; a single-platform classification result cannot justify closed-loop deployment, and a field pilot does not by itself

establish industrial maturity. Table 6 summarizes the minimum data and experimental requirements, validation protocols, mandatory outputs and metrics, and evidence required for progression across the five research stages.

Table 6. Actionable research and validation roadmap for the intelligent reliability of ferrofluid seals.

Research Task	Minimum Data or Experimental Requirements	Validation Protocol	Mandatory Outputs and Metrics	Evidence Required for Progression
Benchmark degradation dataset	Structure and fluid metadata; operating history; core signals; labels; run IDs; intervention records	Run-level training, validation, and test splits; no adjacent windows across splits	Data dictionary; units; synchronization; failure criteria; missing-data and version records	Repeated trajectories across conditions; reproducible state-recognition, cross-condition diagnosis, and RUL benchmark tasks
Cross-condition and external-rig validation	Multiple speed, pressure, temperature, medium, cooling, structure, or rig conditions	Within-condition, held-out-condition, cross-structure, and external-rig tests	Class-wise precision, recall, and F1; confusion matrix; false-alarm and missed-detection rates; cross-condition performance drop; inference latency	Consistent held-out-condition performance with a quantified performance drop and no random-window data leakage
Physically consistent HI validation	Condition-calibrated HI set; baselines; sensor placement; functional-failure links	Repeated runs; condition normalization; comparison with failure criteria	Sensitivity; trend consistency; robustness; repeatability; threshold relevance; uncertainty MAE; RMSE; a justified relative error; early/late prediction bias; prediction-interval coverage and width; calibration; maintenance-risk outputs	Repeatable HI behavior across runs and conditions with a traceable physical link
Uncertainty-aware RUL prediction	Independent run-to-failure trajectories; prediction origin and horizon; failure threshold; censoring	Run-level, held-out-condition, and cross-rig tests where possible	MAE; RMSE; a justified relative error; early/late prediction bias; prediction-interval coverage and width; calibration; maintenance-risk outputs	Calibrated probability output and acceptable maintenance-risk performance
Closed-loop intervention verification	HI or RUL trigger; action logs; baseline and intervention runs; post-action observation	Detect-decide-act-verify; matched repeated controls; stated safety and termination criteria	Pressure, leakage, temperature, torque, life, latency, energy, side effects, durability	Repeatable functional recovery or life benefit without unacceptable side effects
Engineering pilot and specification development	Long-duration or field-oriented operation; complete sensor, intervention, maintenance, cost, authority, and safety records	Application-relevant pilot testing; sensor-drift and missing-channel tests; repeated intervention and maintenance cycles; independent review	Availability; false and missed alarms; sensor drift; maintenance cost; intervention authority; safety events; long-duration performance; reproducible reporting specification	Repeatable pilot evidence across the intended operating envelope and a documented application-specific testing and reporting specification

Note: The roadmap represents evidence-informed minimum reporting and verification recommendations rather than a universally established standard. Requirements should be adapted to the seal structure, dominant failure risk, sensing configuration, and intended engineering application.

7. Conclusions

This review examined the intelligent reliability of ferrofluid seals under complex operating conditions. Degradation arises from coupled factors and ultimately reduces pressure capacity, increases leakage, and shortens useful life. The evidence was organized into a framework linking physical degradation, observable signals, HIs, diagnosis, prognosis, and maintenance decisions.

Direct ferrofluid-seal evidence currently supports the principal ferrohydrodynamic failure mechanisms, pressure and leakage behavior, thermal and liquid-medium degradation, selected torque and AE observations, and limited bench-scale state recognition. Transferable studies from mechanical seals, hydraulic seals, valves, pumps, actuators, and broader PHM systems provide candidate diagnostic, cross-domain learning, degradation, and RUL methods. By contrast, the unified health-indicator portfolio, multisource diagnostic architecture, uncertainty-aware ferrofluid-seal RUL, indicator-triggered maintenance mapping, and automatic closed-loop active control remain proposed concepts requiring direct run-to-failure, cross-condition, and intervention validation.

Material degradation remains comparatively under-observed. Carrier-fluid loss, surfactant deterioration, aggregation, oxidation, contamination, and compatibility-driven property drift can produce overlapping pressure, temperature, torque, and leakage responses, while direct long-duration material-state measurements remain limited.

Several major challenges remain. Public degradation data are scarce, evaluation protocols are inconsistent, HIs lack sufficient physical consistency, and closed-loop health management remains immature. Future studies should directly validate observability-oriented design, physics-informed life prediction, combined online monitoring and periodic fluid verification, and feedback-driven health-management strategies. These efforts could improve seal observability, predictability, and maintainability under complex operating conditions.

This review complements the UHV-focused intelligent-design review [38] by providing a cross-application framework for reliability evidence, monitoring, diagnosis, prognosis, maintenance, and validation. Its principal output is an evidence-to-action framework rather than a UHV-specific design methodology.

The international evidence base spans multiple seal configurations and application contexts, but recent reliability, diagnostic, and material-state studies remain unevenly distributed across laboratories and regions. Independent cross-region, cross-rig, and cross-formulation validation is therefore still needed.

Ferrofluid-seal research is moving beyond performance optimization toward reliability-oriented design and health management. This review provides a structured basis for condition monitoring, health assessment, maintenance planning, and engineering application.

Author Contributions: Conceptualization, J.L. and Z.L.; writing—original draft preparation, J.L.; writing—review and editing, Y.S., S.L., X.Z. and Z.L.; supervision, Z.L.; funding acquisition, Z.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Science Foundation of Qinghai Province, grant number 2025-ZJ-958M.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

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