Review Article

Predictive Maintenance for Immunization Cold-Chain Systems: An Evidence-Informed Narrative Review and Phased Implementation Framework

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Reliable cold-chain equipment is essential for vaccine storage and service continuity, yet corrective and scheduled preventive maintenance may not fully use routine data to identify emerging equipment risk. This review aimed to map routine immunization cold-chain data, examine how they might support earlier identification and management of equipment-failure risk, and develop an evidence-informed implementation framework. An evidence-informed narrative review with structured evidence mapping and conceptual framework development was conducted. PubMed, including MEDLINE, was searched from inception to 18 August 2026, supplemented by searches of WHO, UNICEF, Gavi and PATH websites and reference lists. Eligible evidence was classified as direct immunization evidence, adjacent healthcare-technology evidence, transferable engineering evidence, normative or programme guidance, or authors' conceptual propositions, and synthesized narratively. Of 130 PubMed records identified, 31 were included; 10 official-web sources and six citation-identified sources were additionally retained, yielding 47 sources. Programmes generated useful temperature, equipment, maintenance, power and operational data, but these data were often fragmented or incompletely linked. Direct immunization evidence for advanced predictive-maintenance models was limited, with no prospective multisite external validation against technician-confirmed equipment failures identified. The synthesis suggested that improved data linkage, explainable rule-based alerts and hybrid maintenance approaches are currently more feasible than advanced analytics in many settings. Advanced approaches require adequate data quality, governance, technical capacity, response systems and field validation. The review proposes a four-stage data-to-decision and evaluation framework progressing from data standardization to rule-based alerts, condition-based prioritization and, where readiness permits, predictive analytics. This conceptual, evidence-informed framework

may support programme decision-making but requires prospective, context-specific validation given heterogeneous evidence and cross-sector transfer.

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Introduction

Reliable immunization supply chains preserve vaccine potency and keep vaccines available for routine and outreach services. Cold-chain equipment (CCE) comprises temperature-controlled storage and transport devices, including refrigerators, freezers, cold and freezer rooms, cold boxes, and vaccine carriers, together with associated temperature-monitoring and power components [1][2]. Poor performance can expose vaccines to damaging temperatures and interrupt storage, distribution, or service continuity, particularly where backup capacity, power, transport, spare parts, and technical support are limited [1][3].

Maintenance is therefore essential to CCE reliability. Preventive maintenance comprises scheduled procedures before failure, including inspection, calibration, cleaning, lubrication, or planned part replacement, to reduce failure risk and extend equipment life. Corrective maintenance restores integrity, safety, or performance after failure or breakdown [1]. Both remain necessary: preventive work addresses foreseeable deterioration, whereas corrective repair responds to faults that cannot be prevented or detected beforehand. However, calendar-based schedules may not reflect current condition or contextual risk, while corrective action begins only after failure and can be delayed by weak reporting, scarce technicians, unavailable parts, or difficult access [1].

These limitations now coexist with expanding digital and programme data. Electronic temperature loggers and remote monitoring systems provide time-stamped temperature, alarm, power, and equipment-status data; CCE inventories, asset-management systems, maintenance logs, spare-parts records, and service tickets capture identity, age, location, condition, and repair history [1][2][4]. In Kenya, remote monitoring combined with data-review teams strengthened visibility and use of refrigerator-performance data, showing the value of linking signals with review and response [5]. These data create an opportunity to identify risk earlier and prioritize maintenance by observed condition and likely consequences. Yet temperature traces alone cannot establish whether an excursion reflects equipment failure, unstable power, loading or door-opening practices, or whether staff and technicians responded appropriately and promptly [1][2][5]. Predictive maintenance is defined here as an additional risk-based function that uses current and historical condition data to estimate emerging failure or performance risk and guide timely action. It complements, rather than replaces, preventive and corrective maintenance and does not inherently require artificial intelligence [6].

Immunization-specific evidence for this function remains limited and heterogeneous. Published work centres mainly on temperature monitoring, equipment visibility, and maintenance operations; the smaller fault-detection literature is represented by simulated or prototype studies, leaving prospective validation within national programmes limited [2][5][7][8]. Broader predictive-maintenance research has developed anomaly-detection, fault-classification, prognostic, and scheduling methods, mainly in industrial and engineering environments [6]. These methods cannot be transferred automatically because public-health cold chains differ in equipment mix, power conditions, data completeness, technical capacity, response pathways, and consequences of error [1][6]. The literature remains insufficiently consolidated into an immunization-specific pathway linking routine data streams with prediction targets, maintenance decisions, validation requirements, and programme constraints [1][2][5][6][8].

Accordingly, this evidence-informed narrative review assesses how routinely generated immunization cold-chain data could support a phased transition toward risk-informed CCE maintenance. It maps relevant data sources; identifies maintenance risks and candidate prediction targets; distinguishes direct immunization evidence from transferable evidence and the authors' conceptual propositions; examines implementation, validation, and evaluation requirements; and proposes a phased operational framework progressing from data standardization and explainable rule-based alerts to condition-based maintenance and, where adequately supported and validated, predictive analytics. The manuscript proceeds through Methods, Results, Discussion, Recommendations, and Conclusion, moving from evidence synthesis to interpretation, operational actions, and implications.

Methods

Review design and rationale

We conducted an evidence-informed narrative review with structured evidence mapping and conceptual framework development. This design connected heterogeneous immunization, maintenance, digital-monitoring, asset-management and engineering evidence to programme decisions rather than

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estimating a pooled intervention effect. Reporting was informed by SANRA criteria [9] and selected search-reporting and evidence-flow principles from PRISMA-S [10] and PRISMA-ScR [11]. The review was not a systematic review or formal PRISMA-ScR scoping review. No protocol was prospectively registered. A written search, eligibility and coding specification guided the update.

Review question and analytical scope

The review addressed: What routinely generated data are available within immunization cold-chain systems, which maintenance risks or prediction targets could they inform, and what implementation, validation and evaluation requirements apply to predictive maintenance of cold-chain equipment (CCE)? Using a Population–Concept–Context structure, the population comprised CCE and associated assets; the concept comprised routine data, maintenance risks, targets and data-to-decision pathways; and the context comprised immunization supply chains across geographic and resource settings. Predictive maintenance was treated as an additional risk-based function, not as a synonym for artificial intelligence.

Information sources and search strategy

PubMed/MEDLINE was searched from inception to 18 August 2026. Four searches covered temperature and equipment monitoring; maintenance, repair and asset management; predictive or condition-based maintenance; and transferable healthcare-technology, refrigeration and heating, ventilation and air-conditioning reviews. No database filters were applied; English-language full-text availability was assessed during eligibility review. Official WHO, UNICEF, Gavi and PATH websites were searched using site-restricted queries. The first ten ranked results per query were screened because web-result totals are unstable. Reference lists of included key reviews and guidance were examined. Supplementary Table S1 reports exact strings, dates and yields. Scopus, Web of Science and Google Scholar were excluded because authenticated, reproducible access was unavailable.

Eligibility and evidence selection

Eligible sources were peer-reviewed studies or reviews, official guidance, and substantive programme reports describing a relevant data stream, condition or failure signal, maintenance process, decision target, validation issue or implementation constraint. Direct immunization evidence was eligible across settings, technologies and designs. Healthcare-technology, refrigeration, building-system and industrial evidence was included only for clearly transferable maintenance concepts or methods. Sources were

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excluded if they addressed vaccine formulation, general logistics or passive containers without an extractable CCE maintenance pathway; lacked technical detail; duplicated another record; or had no English full text. Records were deduplicated by PubMed identifier, screened by title and abstract, and assessed in full text. Screening used a single-reviewer process without independent duplication. Full-text exclusion reasons were recorded. The identification and selection of evidence sources are summarized in Figure 1.

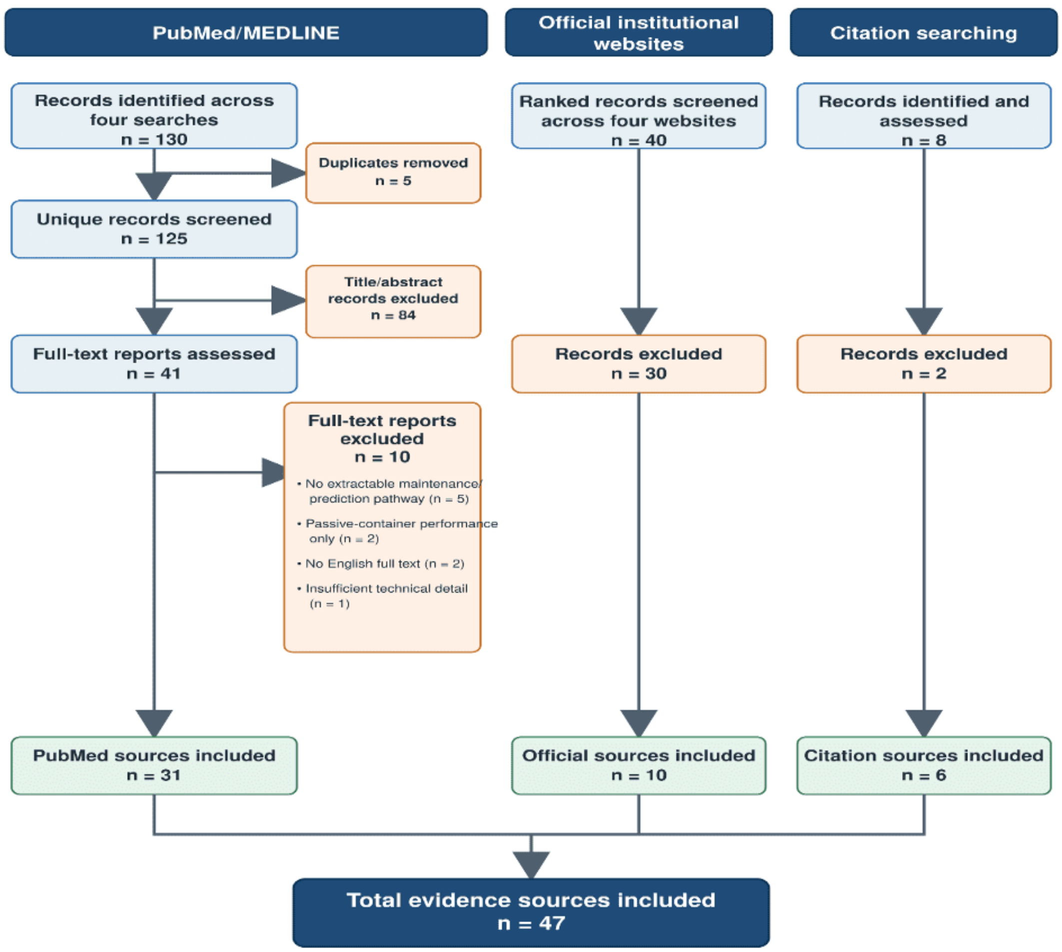

Figure 1. Identification and selection of evidence sources included in the narrative review and structured evidence mapping

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Data extraction, evidence classification and indicator consolidation

Information was charted in a structured evidence ledger covering bibliographic details; country and setting; source and study design; equipment or system; data stream; measurement unit, frequency and granularity; data-quality limitations; contextual variables; maintenance risk or prediction target; decision supported; model or rule, where applicable; validation approach; reported operational outcome; and implementation constraints. Each finding was classified as: direct immunization evidence; adjacent healthcare-technology evidence; transferable engineering evidence; normative or programme guidance; or an authors' conceptual proposition. Conceptual propositions were recorded separately and were not counted as empirical support.

Indicators described under different labels were consolidated only when their operational meaning, measurement basis and decision use were sufficiently equivalent. The consolidation retained distinctions among raw variables, derived indicators, contextual modifiers, prediction targets and maintenance actions. Conflicting definitions or thresholds were preserved rather than averaged. Every consolidated indicator remained linked to its source and evidence class to prevent transferred concepts from being presented as established immunization findings.

Synthesis and framework development

Evidence was synthesized narratively and mapped across data availability, target definition, decision use, validation maturity and programme feasibility. Recurrent relationships were translated into a phased operational framework: data standardization and governance; explainable rule-based alerts; condition-based maintenance using combined condition and context data; and predictive analytics only where labelled outcomes, external validation, workflow integration and monitoring were adequate. Framework elements were included when supported by direct evidence, authoritative guidance or an explicitly identified transferable principle. Recommendations were derived by linking recurrent evidence gaps and implementation constraints to feasible programme actions; they were not treated as estimates of effectiveness or cost-effectiveness.

Evidence appraisal and design boundaries

Because the evidence comprised heterogeneous empirical studies, reviews, guidance and programme reports, no single risk-of-bias instrument or quantitative certainty grading was applied. Sources were instead characterized by design, setting, evidence class, directness to immunization, completeness of methods, validation basis and reported limitations. The synthesis did not pool effects, compare maintenance strategies quantitatively, estimate diagnostic accuracy or costs, or validate algorithms. Its outputs are therefore an evidence map and implementation-oriented conceptual framework, not proof of predictive performance, causal benefit or programme impact.

Results

Evidence selection and characteristics

The database searches identified 130 PubMed/MEDLINE records. After removal of five duplicates, 125 unique records were screened; 84 were excluded by title and abstract, and 41 full-text reports were assessed. Ten full texts were excluded: five lacked an extractable maintenance or prediction pathway, two addressed passive-container performance outside the powered cold-chain equipment (CCE) focus, two lacked English full text, and one provided insufficient accessible technical detail. Thirty-one PubMed sources were included. Separately, 40 ranked records from official websites were screened and 10 retained; eight citation-identified records were assessed and six retained. The synthesis therefore comprised 47 sources (Figure 1).

The evidence set contained 31 sources providing direct immunization evidence, two providing adjacent healthcare evidence, five providing transferable engineering evidence, and nine providing normative or programme guidance. Four sources were published before 2010, 18 during 2010-2019, 24 during 2020-2026, and one official webpage was undated. Direct evidence covered field temperature monitoring, equipment and facility assessments, maintenance operations, programme evaluations, qualitative studies, and analytical or simulation work. It examined facility refrigerators and freezers, transport devices, power systems, and programme-level equipment management across single-country, multicountry, and global settings. Only three sources developed or simulated immunization-specific fault-detection, anomaly-detection, or digital-twin applications [8][12][13]. None reported prospective, multisite external validation against technician-confirmed CCE failures. Supplementary Table S2 provides the complete source-level matrix.

Data sources, prediction targets and maintenance decisions

Direct studies and guidance supported the routine use of temperature, asset, maintenance, power, operational, and consequence data [1][2][3][4][5][7]. Temperature traces identified excursions and abnormal

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patterns, but did not independently establish their cause [2][5][8][12]. The evidence mapping and authors' interpretive synthesis support the proposed data-to-decision relationships in Table 1; the table does not establish their frequency, predictive strength, or causality.

Data domain	Key data inputs	Data source or tool	Potential prediction target or early-warning signal	Maintenance or programme decision supported	Evidence status	Supporting sources
Temperature and equipment performance	Excursions; recovery time; alarms; compressor or sensor signals	Digital data logger; remote temperature monitor; equipment monitor	Recurrent instability, anomalous pattern, or possible fault	Inspect, adjust use, repair, or relocate stock	Direct immunization evidence	[2][5][8][12]
Asset identity and lifecycle	Unique identifier; make/model; age; location; warranty; status	CCE inventory; asset registry; procurement record	Model-, age-, or lifecycle-related risk	Repair, warranty action, replacement, or decommissioning	Direct immunization evidence	[4][14][15]
Maintenance and repair history	Planned service; failures; diagnoses; repeat repairs; closure	Logbook; service ticket; technician report	Recurrent fault or overdue intervention	Prioritize visit; revise service plan; escalate supplier issue	Normative guidance	[1][15][16]
Spare-parts use and procurement	Parts used; stock-outs; lead times; model compatibility	Parts inventory; work order; procurement system	Potential part shortage or recurring component demand	Pre-position or procure parts; review model support	Authors' conceptual synthesis	Operational inputs: [1] [16]
Power and energy reliability	Outages; voltage; battery age;	Power log; voltage monitor;	Power-related instability or autonomy risk	Service power system; prepare	Direct immunization evidence	[7][17]

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Data domain	Key data inputs	Data source or tool	Potential prediction target or early-warning signal	Maintenance or programme decision supported	Evidence status	Supporting sources
	solar or generator status	energy checklist		backup; prioritize off-grid site		
User practices and service operations	Door opening; loading; defrosting; response; supervision	Checklist; observation; supervision record	Operational cause of alarms or delayed response	Correct workflow; train staff; avoid unnecessary dispatch	Normative guidance	[5][18]
Vaccine stock and wastage consequences	Doses stored, exposed, moved, or discarded; session demand	Stock ledger; electronic logistics system; excursion report	Consequence of equipment failure	Prioritize high-consequence sites; arrange safe storage	Direct immunization evidence	[7][19]
Facility access, workforce and equity	Remoteness; travel time; workload; transport; connectivity	Facility list; geographic information system; technician roster	Delayed-response or exclusion risk	Route and prioritize visits equitably	Authors' conceptual synthesis	Operational inputs: [16] [20]
Climate and environmental risk	Heat; floods; dust; humidity; seasonal access	Climate map; site assessment; emergency plan	Environment-related stress or service disruption	Seasonal servicing; contingency preparation	Authors' conceptual synthesis	Operational inputs: [21] [22]

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Table 1. Evidence-linked data domains, prediction targets and maintenance decisions for immunization cold-chain equipment

Candidate analytical and decision approaches

Candidate methods varied by decision and data maturity. Industrial, building-system, and medical-equipment literature described statistical, machine-learning, prognostic, and fault-diagnosis methods [6][23][24][25][26][27]. These methods are transferable concepts, not validated immunization findings. Multi-criteria decision-making ranks actions after risks are estimated; it does not itself predict equipment failure.

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Operational use case	Candidate analytical approach	Minimum data requirements	Model output	Validation requirement	Evidence status	Supporting sources
Alert triage	Explainable thresholds or composite risk score	Validated limits; timestamped alarms; operating context	Alert and reason code	Compare alerts with review and technician findings	Normative guidance	[2][18]
Unusual-pattern detection	Isolation forest; one-class support vector machine; autoencoder; convolutional neural network	Representative time series; normal-operation data; labelled faults where available	Anomaly or fault score	External, prospective testing across models and settings	Direct immunization evidence	[8][12]
Instability or demand forecasting	Autoregressive integrated moving average; recurrent or long short-term memory network	Regular longitudinal temperature, power, or parts series	Forecast and uncertainty interval	Temporal holdout; calibration; operational usefulness	Transferable engineering evidence	[6][23][27]
Failure-risk estimation	Logistic regression; Cox model; random forest; gradient boosting	Unique assets; covariates; dated failures; censoring information	Failure probability or time-to-event risk	Discrimination, calibration, transportability, subgroup performance	Transferable engineering evidence	[6][24][25]
Degradation or remaining useful life	Regression or prognostic model	Repeated condition signals; maintenance history;	Condition trend or remaining-life estimate	Error and uncertainty against observed degradation or failure	Transferable engineering evidence	[24][25][26]

doi.org/10.32388/28D74O.2

Operational use case	Candidate analytical approach	Minimum data requirements	Model output	Validation requirement	Evidence status	Supporting sources
		degradation endpoint				
Maintenance prioritization	Transparent multi-criteria scoring	Estimated risk; vaccine consequence; access; equity; cost; technician capacity	Ranked work list with rationale	Prospective workflow, equity, and response evaluation	Authors' conceptual synthesis	Operational factors: [1][16][20]

Table 2. Potential analytical approaches and validation requirements for predictive maintenance

Implementation gaps and evaluation framework

The mapping identified incomplete and non-standardized records, fragmented systems, missing equipment identifiers, inconsistent failure classifications, and weak linkage between temperature signals and technician-confirmed faults [1][4][15][16]. Limited interoperability, sparse immunization-specific model validation, unclear governance, and constraints in technicians, connectivity, financing, transport, and spare parts further restrict action [20][28][29][30]. Remote, off-grid, or climate-exposed facilities may also be less visible in digital datasets [17][20][21][22]. Data ownership, privacy, and cybersecurity require explicit governance when asset and monitoring platforms are linked [13][28]. A technically accurate alert has limited programme value if responsibility, parts, transport, or technician capacity do not permit a timely response [5][16][20]. Table 3 therefore couples predictive performance with maintenance, programme, economic, feasibility, and equity outcomes.

Evaluation domain	Indicator	Definition or calculation	Data source	Interpretation	Evidence status
Maintenance performance	Uptime/downtime; failure rate; mean time between failures; mean time to repair; repeat failure/repair; response time; completion; backlog	Available and unavailable time; failures per asset-time; operating or repair time per event; repeats within a defined window; alert-to-response time; completed and open work orders	Asset registry; monitor; work order; technician record	Whether alerts improve reliability and maintenance execution	Authors' conceptual synthesis; informed by [1][15][16]
Predictive or alert performance	Sensitivity/recall; specificity; precision/positive predictive value; false-alarm rate; area under the receiver operating characteristic curve; calibration; warning lead time; alerts with confirmed outcomes	Standard classification measures; agreement between predicted and observed risk; alert-to-fault interval; confirmed outcomes divided by alerts	Alert log; model output; technician-confirmed outcome	Accuracy, reliability, timeliness, and verifiability without preset thresholds	Authors' conceptual synthesis; informed by [6][8][12][25]
Immunization-programme consequences	Excursions; doses exposed, relocated, or discarded; failure-attributable wastage; cancelled sessions or interruptions; stock availability; time to	Event counts, affected doses, service availability, restoration interval, and comparison by	Temperature and excursion records; stock system; session report; facility and geographic data	Whether maintenance performance translates into programme protection and	Authors' conceptual synthesis; informed by [5][7][19][20]

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Evaluation domain	Indicator	Definition or calculation	Data source	Interpretation	Evidence status
	restore safe storage; response equity	remoteness or climate exposure		equitable response	
Economic and feasibility measures	Maintenance/repair, emergency transport, connectivity, and data-system costs; parts use; technician time/travel; cost per failure or downtime day avoided; acceptability; sustainability	Resource use and costs over a defined period; incremental cost divided by failures or downtime avoided; structured user and system assessments	Finance; procurement; parts; transport; workforce; implementation records	Affordability and feasibility; does not establish cost-effectiveness without comparison	Authors' conceptual synthesis; informed by [1][16][30]

Table 3. Evaluation framework for predictive maintenance in immunization cold-chain systems

Phased data-to-decision framework

The evidence mapping and identified gaps support a four-stage authors' interpretive framework. Stage 1 standardizes a minimum dataset, assigns unique equipment identifiers, and links temperature, asset, repair, power, stock, and facility records. Stage 2 applies explainable rule-based alerts using locally verified operational thresholds and documented escalation routes. Stage 3 uses condition-based maintenance and multi-criteria prioritization to combine equipment risk with vaccine consequences, feasibility, remoteness, and equity. Stage 4 introduces predictive analytics only when data quality, technician-confirmed outcomes, governance, response capacity, and prospective validation are adequate. Figure 2 closes the pathway by feeding confirmed diagnoses and maintenance outcomes back into data checks, rules, scores, and models. This progression was not derived from source-frequency analysis or comparative-effectiveness testing. It complements rather than replaces preventive and corrective maintenance, and advancement depends on demonstrated system readiness and validation.

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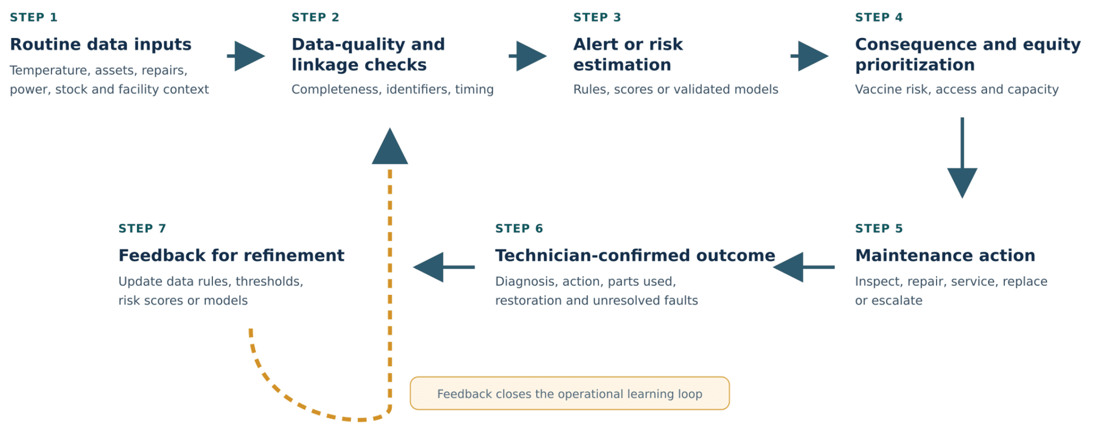

Figure 2. Proposed data-to-decision pathway for predictive maintenance of immunization cold-chain equipment

Routine data inputs → data-quality and linkage checks → alert or risk estimation → consequence and equity prioritization → maintenance action → technician-confirmed outcome → feedback for rule or model refinement. The feedback loop returns confirmed outcomes to the linkage and refinement steps.

Discussion

Principal interpretation and contribution

Returning to the review objective, the synthesis indicates that immunization programmes already generate data that could support earlier maintenance decisions, but these data are fragmented and vary in completeness, quality and actionability. Direct immunization evidence supports temperature monitoring, equipment visibility, structured data review and maintenance operations more clearly than advanced predictive modelling [1][2][4][5][15][16][18][20][30]. The latter is represented by a small number of immunization-specific development or simulation studies and mainly by transferable engineering evidence [6][8][12][13][23][24][25][27]. Accordingly, the four-stage pathway is an evidence-informed interpretive framework requiring prospective validation. Its contribution is not new data streams, but their integration into an immunization-specific pathway connecting data quality, risk identification, programme consequences, maintenance prioritization, technician-confirmed outcomes and evaluation.

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Evidence convergence, divergence and transferability

Across evidence types, there is convergence around longitudinal condition monitoring, linkage with maintenance histories, detection of abnormal or deteriorating behaviour, confirmation of failures and progressive movement from rules towards more advanced analytics [5][6][8][12][15][18][23][24][25]. The operating conditions nevertheless diverge substantially. Industrial and building systems may provide high-frequency measurements, relatively standardized assets and larger labelled failure datasets; immunization systems often combine heterogeneous equipment with incomplete records, intermittent connectivity, sparse confirmed failures and limited technician coverage [1][4][15][20][23][27][29][30]. Moreover, CCE failure occurs within public-health programmes and may affect vaccine integrity, stock availability, service continuity and equitable access [5][7][19][20]. Industrial or medical-equipment methods therefore define candidate approaches, not directly deployable immunization models; transfer requires contextual adaptation and validation.

Operational applicability, hybrid maintenance and system context

Predictive maintenance is most defensible as one component of a hybrid maintenance system. Corrective maintenance remains necessary for unanticipated failures and emergency restoration, while preventive maintenance addresses scheduled servicing, safety and manufacturer requirements [1]. Condition-based maintenance brings forward intervention when observable deterioration or recurrent alarms justify action; predictive maintenance additionally requires adequate longitudinal data and validated failure outcomes. Risk-based or multi-criteria prioritization then allocates technicians, transport and spare parts among competing needs, but does not itself predict failure.

Applicability will vary between facility refrigerators, walk-in cold rooms and more complex equipment; grid-connected, unstable-power and solar direct-drive settings; central stores and remote facilities; and systems with or without backup capacity [15][17][20][21][22]. Ownership may also affect data access and accountability. Maintenance priority should therefore reflect both failure probability and consequence, including vaccine quantity or scarcity, alternative storage, service volume, remoteness, campaign or outbreak requirements and equity. These dimensions are authors' conceptual synthesis and require operational testing.

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Validation, feasibility, limitations and research gaps

Discrimination measures alone cannot establish programme benefit. Prospective studies should examine calibration, false alarms, missed failures, warning lead time and technician-confirmed outcomes, and compare performance with existing preventive and corrective maintenance [6][8][12][13][24][25]. Multi-criteria prioritization requires separate assessment because it organizes action rather than validates prediction. Even an accurate alert has little value without functioning escalation, technicians, transport and spare parts [5][16][20].

Implementation depends on unique equipment identifiers, standardized failure categories and interoperable linkage among temperature systems, asset registries, maintenance platforms, electronic logistics management information systems and technician records [1][4][16][28][29]. National governance must address data ownership, privacy, cybersecurity, vendor dependence, workforce capacity, connectivity and sustained financing. Evaluation should examine false alarms and alarm fatigue, false negatives, model drift, transportability across equipment and countries, and bias or exclusion when remote facilities generate less complete digital data. Potential benefits must be assessed against the incremental costs of monitoring hardware, connectivity, integration, analytics, training, parts, transport, governance, model maintenance and decommissioning [14][16][20][30].

This review is limited by its narrative design, documented search scope, heterogeneous evidence, absence of formal quality appraisal, scarcity of direct predictive-maintenance studies, reliance on transferred concepts, and lack of pooled effectiveness, cost-effectiveness or externally validated estimates. Generalizability across equipment, countries and supply-chain structures is therefore uncertain. Research priorities include standardized equipment and failure datasets, technician-confirmed labels, prospective comparisons of hybrid approaches with current maintenance, external and temporal validation, and evaluation of downtime, vaccine consequences, cost, feasibility, acceptability, scalability and equity. These gaps provide the basis for the subsequent Recommendations section.

Recommendations

Predictive maintenance should be developed as an extension of existing preventive and corrective maintenance systems, with implementation matched to programme readiness. Countries should first establish usable equipment data, functioning maintenance workflows and response capacity. Explainable alerts and condition-based approaches can then be piloted within existing systems. Advanced predictive

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analytics should proceed only after prospective validation demonstrates acceptable performance, operational feasibility and added programme value against the current maintenance baseline.

Phase and documented gap	Priority actions	Lead responsibility	Readiness and monitoring	Evidence basis
1. Establish foundations: incomplete inventories and identifiers; inconsistent failure categories; fragmented records; weak feedback and ownership	Define a minimum cold-chain equipment (CCE) dataset; assign unique identifiers; standardize fault, repair and outcome categories; link temperature, inventory, maintenance, parts and power records; assign governance and escalation; require technician-confirmed closure.	National programme; technicians and information-system teams support	Monitor identifier validity, field completeness, confirmed outcomes and record linkage.	Gaps [1][4][15][16][28][29]; evidence-informed authors' recommendation.
2. Introduce explainable alerts and hybrid maintenance: reactive or calendar-based workflows; unresolved alarms; constrained response resources	Develop context-specific rules; test thresholds locally; define escalation; integrate alerts with preventive and corrective workflows; prioritize by equipment risk, vaccine consequences, remoteness, power or climate exposure and equity; coordinate technicians, transport and parts.	National and subnational managers, technicians and logisticians	Monitor review, response time, confirmed outcomes, false alarms, missed failures, completion, backlog and downtime.	Constraints [2][5][16][18][20]; evidence-informed authors' recommendation.
3. Conduct prospective pilots and economic evaluation: limited validation;	Pilot defined cohorts; prespecify targets, comparators and thresholds; compare with existing maintenance;	Programmes, researchers, implementers, technicians and	Require identifiers, outcome capture and response capacity; use Table 3 indicators without	Validation gaps [6][8][12][13][24][25]; evidence-informed authors' recommendation.

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Phase and documented gap	Priority actions	Lead responsibility	Readiness and monitoring	Evidence basis
uncertain feasibility, costs and programme value	confirm outcomes technically; assess Table 3 domains; document costs, workforce needs and unintended consequences.	independent evaluators	unsupported thresholds.	
4. Governed scale-up: premature adoption; governance, vendor, cybersecurity, transferability and digital-exclusion risks	Validate across equipment and settings; monitor calibration, subgroup performance and drift; retain human oversight; define review and retraining; require data portability and transparent vendor terms; include low-connectivity facilities and recurrent costs.	Health, digital-health, cybersecurity and procurement authorities; partners support	Scale only after foundations function; performance, operational value, costs, financing, privacy, accountability and equitable coverage are demonstrated or documented.	Governance gaps [13][17][20][21][22][28][30]; evidence-informed authors' recommendation.

Table 4. Phased recommendations for advancing predictive maintenance of immunization cold-chain equipment

A practical implementation pathway would begin with data standardization and data triangulation, followed by simple escalation rules for repeated excursions, delayed recovery, repeated repairs, missed preventive maintenance, unstable power and difficult technician access. Predictive algorithms and artificial intelligence should be introduced only after unique equipment identification, maintenance documentation, technician feedback loops and governance systems are functional.

Conclusion

This review mapped how routinely generated immunization cold-chain data could inform earlier identification and management of equipment-failure risk. Immunization programmes generate potentially useful operational data, but direct evidence validating advanced predictive-maintenance models in vaccine supply chains remains limited. The most feasible near-term approach is to improve data quality and linkage, apply interpretable risk indicators, and combine data-informed alerts with established preventive and corrective maintenance and technician judgement. Conclusions are constrained by limited direct immunization evidence, heterogeneous sources, reliance on concepts transferred from other sectors, and the absence of prospective effectiveness or economic validation. Future research should prospectively evaluate context-specific approaches using linked equipment and maintenance data, technician-confirmed outcomes, and comparisons with existing practice, while assessing operational, economic and equity outcomes. Advanced analytics should complement, not replace, established maintenance and should be introduced only where data quality, governance, technical capacity and response pathways are adequate.

Notes

The following references are included in the supplementary file: [31][32][33][34][35][36][37][38][39][40][41][42][43][44][45][46][47][48][49][50]

Statements and Declarations

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Potential Competing Interests

No potential competing interests to declare.

Use of Generative AI

Generative AI tools (OpenAI ChatGPT) were used to assist with language editing, structural refinement, and improving clarity. All scientific content, interpretations, references, and final text were critically reviewed and verified by the authors, who take full responsibility for the manuscript.

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