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**Artificial intelligence and optimization of the vaccine supply chain in Morocco:
economic efficiency, territorial equity, and health system resilience**

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ABSTRACT

Vaccination programmes depend on supply chains that forecast needs, preserve product quality, avoid stockouts, and deliver doses on time. This structured narrative review examines documented uses of artificial intelligence and digital technologies in vaccine supply chains and proposes a framework for Morocco. Ten PubMed searches (January

2023–September 2026) yielded 774 records and 579 unique PMIDs; two-stage screening retained 71 core and 63 contextual references. The evidence is uneven: registries and logistics information systems have field evaluations, whereas AI-based forecasting, cold-chain anomaly detection, and predictive maintenance rest mainly on retrospective or simulated validation, and no field evaluation of AI-based geospatial prioritization was found. We propose a four-layer conceptual framework (data, interoperability and governance,

analytics, human decision) with explicit equity constraints, and a phased roadmap that compares AI with digitization alone before any scale-up. The framework has not yet been validated in Morocco.

Keywords: Artificial intelligence; vaccine supply chain; cold chain; territorial equity; Morocco.

1. Introduction

Vaccination is one of the most effective public health interventions, but its impact depends on a supply chain capable of making quality products available at the right place, time, and quantity. The Immunization Agenda 2030 places equitable access, people-centred systems, and data use among the decade's priorities [1]. The vaccine chain covers needs estimation, procurement, storage, thermal preservation, transport, distribution, administration, and wastage monitoring; a failure at any level can cause stockouts, overstocking, expiry, temperature excursions, or vaccination delays.

Constraints are particularly acute in low- and middle-income countries, where geographic heterogeneity, storage capacity, energy, transport, and fragmented information systems complicate coordination [2, 3]. Simulation work in Benin and Mozambique shows that reorganizing distribution tiers and delivery routes can increase availability while reducing the logistics cost per dose [4, 5], demonstrating the value of quantitative tools for testing scenarios before investment. The cold chain remains a critical link: temperature deviations cause financial losses, reduced availability, and loss of trust [6, 7]. Connected sensors and the Internet of Things now offer real-time visibility, and artificial intelligence can exploit these data streams to detect anomalies, anticipate failures, or recommend action [8].

Here, artificial intelligence refers to analytical tools — machine learning, forecasting, optimization, anomaly detection, and geospatial analysis — capable of supporting a logistics decision, and is not limited to generative artificial intelligence [9, 10]. Morocco has significant assets: a long-standing national immunization programme [11], experience with mass COVID-19 vaccination, and investments in digital transformation [12], but the presence of digital solutions does not guarantee their interoperability or the quality of decisions [13]. To our knowledge, no synthesis focuses specifically on the transferability to Morocco of artificial intelligence applications to the vaccine supply chain while integrating performance, cost, equity, and resilience. This review therefore pursues two objectives: to synthesize the uses and lessons available in the open and institutional literature, and to

propose a conceptual framework adapted to the Moroccan context, to be validated before any implementation.

2. Background and related work

Recent literature on digital vaccine supply chains clusters around four contributions. First, electronic immunization registries and logistics management information systems improve stock visibility and operational decision-making, although their cost and effectiveness depend on actual data use [14, 15, 16]. Deployments in Ethiopia, India, and Cameroon illustrate both the operational gains and the persistent constraints in connectivity, training, and data-entry quality that limit their reach [17, 18, 19].

Second, architectures combining sensors, platforms, blockchain, and machine learning target cold-chain integrity and product authenticity [20, 21]. Third, forecasting applications increasingly draw on machine learning and large language models to refine demand and resupply calculations, including in Mozambique [22, 23, 24, 25]. Fourth, a smaller body of work addresses equity and governance directly, proposing protocols for fair allocation under scarcity and ethical principles for artificial intelligence in health [26, 27].

Across these strands, African real-world evidence remains scarcer than conceptual or simulation-based publications, and comprehensive economic evaluations — covering integration, connectivity, training, and maintenance costs — are rare [28, 29, 30, 31]. International guidance from the World Health Organization's digital health strategy [32], VillageReach's equity guide [33], and Gavi's zero-dose and supply-chain resources [34] provide normative anchors but require local adaptation. This gap — between a growing global evidence base and its translation into an evaluable, Morocco-specific framework — motivates the method described below.

3. Methods

We conducted a structured narrative review, reflecting the emerging and heterogeneous nature of the field, which combines empirical studies, modelling, technological frameworks, and institutional documents; the review does not claim the exhaustiveness of a systematic review and does not include a meta-analysis.

The main search covered publications from January 1, 2023 to September 14, 2026; all ten PubMed searches were run on September 14, 2026. They combined three concept blocks — vaccination or immunization; supply chain, stock, distribution, transport, or cold chain; and artificial intelligence, machine learning, predictive analytics, Internet of Things, blockchain, digital twin, or logistics information

system — together with targeted searches on Africa and Morocco, resilience, economics, equity and governance, implementation, and forecasting. The full search strings, run dates, and record counts are given in Supplementary Table S1. Grey literature was searched separately on the websites of the World Health Organization, UNICEF, Gavi, the World Bank, VillageReach, and Moroccan institutional portals; it is used as normative or contextual material, not as evidence of effectiveness. References published before 2023 [3, 4, 5] are not part of the screened corpus; they are background references, cited only to frame the problem in Sections 1 and 2.

The ten searches yielded 774 records, corresponding to 579 unique PMIDs after removal of 195 duplicates (450 with a PubMed Central identifier). The core corpus required an explicit link between a vaccine supply chain function — forecasting, stock, cold chain, transport, distribution, allocation, traceability, or logistics information system — and an artificial intelligence or Industry 4.0 technology; the contextual corpus was limited to work providing indispensable data on costs, resilience, cold chain, or implementation in Africa and low- and middle-income countries; records addressing neither were excluded. Screening proceeded in two stages (Figure 1). In the preparatory stage, titles and abstracts were classified as core (66), contextual (43), or excluded (437), and 33 uncertain records were adjudicated on the full text (10 core, 16 contextual, 7 excluded), giving 76 core and 59 contextual references and 444 exclusions. In the second stage, a second reviewer independently re-screened all 444 exclusions and re-read the included references. This identified four false negatives (re-included), one duplicate publication indexed under two PMIDs (removed), and seven reclassifications: four included references excluded and three moved between the core and contextual corpora. The final corpus comprised 71 core and 63 contextual references; of the 578 unique publications screened, 444 were excluded. A PMID-level decision log (initial and final classification, reason, adjudicator) is provided as Supplementary File S2.

For each core reference, we extracted the setting, supply chain function, technology, data requirements, indicators, reported benefits, limitations, and transferability, and recorded whether the reported benefit was attributable to artificial intelligence or to digitization in general. We graded the level of validation as (A) evaluation in routine operations; (B) retrospective validation on real programme data; (C) simulation, modelling, or synthetic data; or (D) architecture, framework, protocol, demonstration, or guidance without original performance data. The reference list cites only the studies that support specific statements; the complete graded corpus is available in

Supplementary File S2. The proposed Moroccan framework results from triangulating these findings with the digital capacities described in the Moroccan literature and international principles of digital health and artificial intelligence ethics [27, 32].

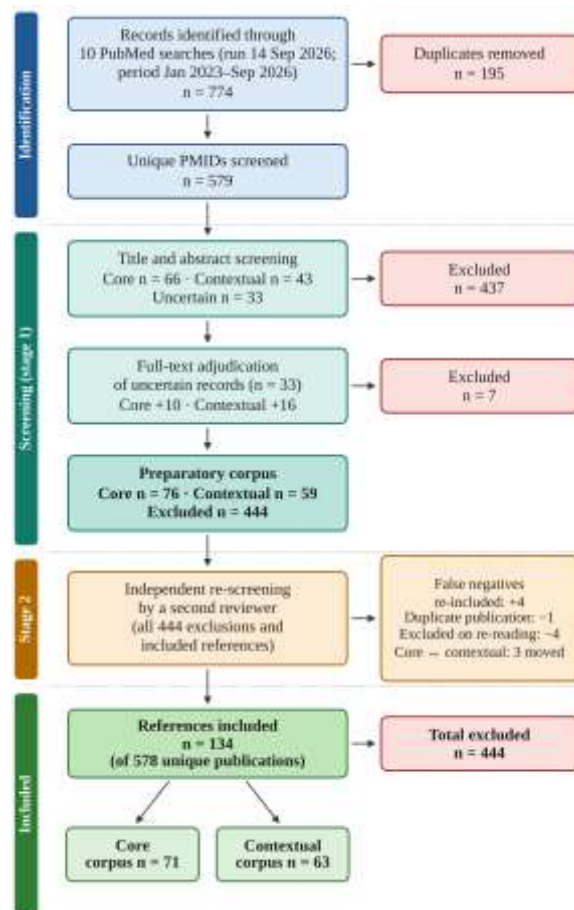


Figure 1. Selection flow diagram.

4. Results

Demand forecasting is the function most often associated with machine learning, but the strength of the evidence depends on the method. In Mozambique, a conventional analysis of routine facility data showed that population-based forecasts under-supplied facilities by about 20% on average (range 5–41%), whereas forecasts based on doses administered were closer to need [22]; the gain came from better use of existing data, not from artificial intelligence. Forecasting with large language models has so far been validated retrospectively on historical demand series [23], and we found no study showing that an AI forecast reduced stockouts or wastage in routine use. Data quality is a binding constraint: a stockout depresses recorded consumption, which a model may misread as low demand, so ordering rules (minimum levels, buffer stocks, lead times) and human review must remain in place.

For cold-chain monitoring, connected sensors recording temperature, power, door openings, and location allow anomaly detection and prioritized intervention, but the reviewed contributions are architectures and demonstrations [8, 9]: their documented contribution is visibility, while large-scale validation and cost-effectiveness remain to be established. Predictive maintenance is less mature still: the fault-detection model of Abhiraman et al. [21] was trained and tested on simulated refrigerator data. For distribution, computational modelling in Benin and Mozambique showed that redesigning tiers and routes could raise availability and lower the cost per dose [4, 5]; these were optimization and simulation models rather than artificial intelligence, and they illustrate the value of testing scenarios before investing. Where field evidence exists, it concerns digitization: electronic registries and logistics information systems improved stock data and were associated with fewer reported stockouts, but data accuracy fell where paper and electronic systems ran in parallel [14, 17].

Table 1. Potential applications and indicators by vaccine chain function.

Function	Application	Main data	Indicators
Estimation	Probabilistic demand forecasting	Cohorts, consumption, coverage, seasonality	Forecast error; bias
Stock	Assisted ordering and redistribution	Stock, batches, expiry, lead times	Stockouts; wastage; service level
Cold chain & maintenance	Anomaly detection, alerts, and failure-risk estimation	Temperature, power, door openings, sensor history	Excursions; response time; availability
Transport	Multi-objective route optimization	Routes, volumes, capacity, weather	Cost/dose; lead time; thermal risk
Equity	Geospatial prioritization	Coverage, distance, vulnerability	Urban-rural gap; zero-dose

Table 2 grades the evidence behind each application. Maturity is uneven: field evaluations exist mainly for digitization, AI-based forecasting and fault detection rest on retrospective or simulated validation, and for AI-based geospatial

prioritization we found operational guidance [33, 34] but no field evaluation in low- and middle-income settings. Benefits observed after digitization should therefore not be attributed to artificial intelligence, and high predictive accuracy does not by itself demonstrate fewer stockouts, lower costs, or narrower territorial gaps.

Table 2. Strength of evidence by application in the reviewed literature.

Application	Representative evidence	Validation level	Not yet demonstrated
Registries and logistics information systems (digitization)	Mekonen et al. [17]; Mantel et al. [14]; Zarekar et al. [15]	A — field evaluations (cross-sectional, pre-post, meta-analysis)	Effect attributable to AI; sustained data use
Demand forecasting	Prosser et al. [22], conventional; Chen et al. [23], large language model	B — retrospective validation on real data	Fewer stockouts or less wastage in routine use
Cold-chain monitoring	Hu et al. [9]; Jiang et al. [8]	D — architectures and demonstrations	Large-scale validation; cost-effectiveness
Predictive maintenance	Abhiraman et al. [21]	C — model trained on simulated data	Performance on field equipment data
Route and network optimization	Lee et al. [4, 5]; Dey et al. [25]	C — computational modelling, largely non-AI	Field implementation; added value of AI
Geospatial prioritization	Gavi Zero-Dose Learning Hub [34]; VillageReach [33]	D — operational guidance; no field evaluation found	Effect on reaching zero-dose children

Note. A = evaluation in routine operations; B = retrospective validation on real programme data; C = simulation, modelling, or synthetic data; D = architecture, demonstration, protocol, or guidance without original performance data.

5. Contribution and implications

5.1. Positioning of the Proposed Framework

This review contributes to information systems research and practice in two ways. First, it grades a fragmented literature by level of validation and separates the effects of digitization from those of artificial intelligence, showing that field evidence is concentrated on registries and logistics information systems while AI applications remain largely retrospective, simulated, or conceptual (Table 2). Second, it proposes a conceptual framework for Morocco (Table 3). Existing work offers technology architectures [8, 9], optimization models [25], or evaluations of digitization [14, 28]; the framework combines four elements that these do not: entry conditions for each layer derived from the evidence, equity encoded as optimization constraints, an evaluation design that isolates the incremental effect of AI, and explicit human accountability. Each layer answers a finding of the review: Layer 1 the dependence of forecasts on data quality [22]; Layer 2 the accuracy losses of parallel paper and electronic systems and weak interoperability [14]; Layer 3 the gap between retrospective and operational validation [21, 23]; and Layer 4 the principle that high-impact decisions — redistribution, territorial prioritization, or route changes — remain validated by an identified responsible party [27]. The framework is a proposal: it has not been deployed, calibrated, or evaluated in Morocco.

Table 3. Proposed four-layer conceptual framework for Morocco.

Layer	Content	Governance focus
1. Data	Consumption, stock, batches, temperatures, equipment, coverage, population, geography	Data quality and ownership
2. Interoperability	Standards, identifiers, quality control, integration across systems	Interoperability and security
3. Analytics	Forecasting, anomaly detection, optimization, scenario comparison	Explainability and validation
4. Decision	Human decision, action, monitoring, and reassessment	Accountability and equity checks

Table 4. Phased implementation roadmap.

Phase	Action	Progression criterion
1. Diagnosis	Audit data on consumption, stock, batches, temperatures, equipment, routes, costs, and target and zero-dose populations; map who holds each dataset	Minimum dataset, data owners, and access rights confirmed
2. Harmonization	Agree shared identifiers (facilities, products, batches), indicators, interfaces, and quality controls; check compliance with Law No. 09-08	Interoperability tested; data-protection requirements met
3. Comparative pilot	Compare current practice (S0), digitization alone (S1), and digitization with AI (S2) in urban, rural, and hard-to-reach districts	S2 improves on S1 without breaching equity constraints
4. Evaluation	Measure costs, logistics outcomes, equity constraints, acceptability, bias, and safety	Incremental value of AI demonstrated; risks controlled
5. Scale-up	Deploy in waves with training and support	Stable performance and sustained governance

5.2. Economic Evaluation

No economic gain from artificial intelligence has been demonstrated in Morocco, and international evidence mostly concerns digitization. In four countries, the per-facility cost of electronic immunization data systems was higher than paper in Honduras and Rwanda, lower in Tanzania, and not significantly different in Guinea, largely because paper workflows continued alongside electronic ones; annual data-management costs represented 0.7–7.7% of national immunization spending [28]. The expected benefits of the framework must therefore be tested rather than assumed. We propose a pragmatic 12-month pilot comparing three arms — current practice (S0), digitization without advanced analytics (S1), and digitization with AI (S2) — from a health-system perspective. Costs would cover procurement, integration, connectivity, training, cybersecurity, and maintenance, separating investment from recurrent costs; outcomes would include cost per usable dose delivered, stockout days,

wastage, delivery time, and temperature excursions. The incremental cost per additional usable dose delivered and per stockout-day averted (S2 versus S1), a budget-impact analysis, and sensitivity analyses would quantify the added value of AI. These are logistics outcomes; translating them into health gains such as disability-adjusted life years averted would require an additional epidemiological model.

5.3. Territorial Equity and Resilience

For equity, average performance can mask access losses: a model trained on doses administered reproduces existing access barriers unless unmet demand, remoteness, and vulnerability are modelled explicitly. We therefore propose that allocation and routing decisions minimize total logistics cost subject to explicit equity and resilience constraints, given in Equations (1) to (4):

$$a_{it} \geq \alpha_i d_{it} \quad (1)$$

$$a^z_{it} \geq \beta_i z_{it} \quad (2)$$

$$T_i \leq T_i^{\max} \quad (3)$$

$$a_{its} \geq \gamma \alpha_i d_{it} \quad (4)$$

where a_{it} is the number of usable doses available in territory i during period t ; d_{it} the forecast demand; α_i the minimum availability ratio; a^z_{it} the doses reserved for reaching zero-dose children and z_{it} their estimated number; β_i the zero-dose priority ratio; T_i the delivery time and $T_i^{\max}$ its maximum; s a disruption scenario (power cut, road closure, supply delay); and γ the share of service maintained under disruption. These constraints apply together with inventory, storage, cold-chain capacity, and budget constraints. Varying α , β , γ , and $T^{\max}$ traces a cost–equity Pareto frontier that shows what each additional unit of equity costs, so that programme managers, with local professionals and communities, set the trade-off explicitly rather than leaving it to the algorithm. Two cautions apply: doses made available are not doses administered, so coverage must be measured separately; and the model has not been calibrated with Moroccan data.

5.4. Implementation in Morocco

Implementation in Morocco would rely on existing institutions rather than a new structure. Indicatively, the Ministry of Health and Social Protection, through the national immunization programme, would own logistics data and validate allocation rules; regional health structures, including the territorial health groups being established under the current reform, would host pilots and validate territorial thresholds; and the national data-protection authority (CNDP)

would review data processing under Law No. 09-08 [35]. These roles are indicative and must be confirmed with the institutions concerned. Data stewardship must define purpose, responsibilities, access rights, retention, and incident management [32]. Practical constraints include uneven connectivity, the coexistence of paper and electronic records, staff workload, and the procurement and maintenance of sensors; none of the proposed architecture is assumed to be operational today.

5.5. Limitations

Limitations of this review include its narrative rather than systematic design; a search limited to PubMed, which may under-represent engineering and operations research literature indexed in Scopus or IEEE Xplore; the inclusion of online-first articles; methodological heterogeneity across studies, which precludes meta-analysis; and the absence of primary Moroccan data on logistics costs and temperature excursions, which prevents the quantification of expected gains.

6. Conclusion

Artificial intelligence can support the modernization of Morocco's vaccine supply chain, but current evidence supports digitization more firmly than artificial intelligence itself. Priority uses — demand forecasting, stockout prevention, cold-chain monitoring, and distribution optimization — should be scaled up only after a pragmatic pilot comparing current practice, digitization alone, and digitization with AI across urban, rural, and hard-to-reach districts, with equity constraints, an economic evaluation protocol, and an algorithmic audit defined before deployment.

Declarations

Originality. This manuscript has not been published and is not under consideration elsewhere.

Ethics. This review analyses published literature only and did not involve human participants or primary data collection; no ethics approval was required.

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Conflicts of interest. The authors declare no conflict of interest.

Data availability. The search strings and record counts (Supplementary Table S1) and the PMID-level screening log (Supplementary File S2) are provided as supplementary material; all cited sources are publicly accessible.

Generative AI use. During the preparation of this work, the authors used Claude (Anthropic) for language editing, translation from French, and restructuring of drafts. The authors reviewed and edited all output, verified every citation against the original source, and take full responsibility for the content of the publication.

Author contributions (CRediT). Ayoub Ellassali: conceptualization, methodology, literature search and data curation, formal analysis, writing – original draft, project administration. Maroua Barha: methodology, investigation (screening and adjudication), data curation, writing – review and editing. Anas El Anssari: investigation (literature search), validation (appraisal of the evidence). Aida Soulaymani: conceptualization, supervision, validation, writing – review and editing.

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