INTERNATIONAL JOURNAL OF SOCIAL SCIENCES BULLETIN
ISSN: (E) 3007-1917 (P) 3007-1909

Volume 4, Issue 1, 2026

ARTIFICIAL INTELLIGENCE–ENABLED DIGITAL TRANSFORMATION IN PAKISTAN'S IMMUNIZATION PROGRAM: THE ROLE OF ORGANIZATIONAL READINESS AND DATA-DRIVEN STRATEGIES ON PROGRAM PERFORMANCE

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DOI: https://doi.org/10.5281/zenodo.22810040

Received	Accepted	Published
25 November 2025	18 January 2026	31 January 2026

ABSTRACT

Artificial intelligence (AI) is increasingly transforming health systems by enabling predictive analytics, intelligent decision support, automated data processing, and more targeted service delivery. In Pakistan, where routine immunization has made important progress but continues to face challenges related to zero-dose children, delayed vaccination, fragmented information systems, geographic inequalities, workforce constraints, and uneven institutional capacity, AI-enabled digital transformation offers a potential pathway for improving program performance. This qualitative study examines the role of organizational readiness and data-driven strategies in enabling AI-supported transformation of Pakistan's immunization program. Drawing on secondary sources, including peer-reviewed literature, policy documents, institutional reports, and evidence on Pakistan's digital immunization initiatives, the study uses qualitative document analysis and thematic synthesis to examine the technological, organizational, workforce, data, governance, and environmental conditions necessary for effective AI adoption. The analysis is guided primarily by the Technology–Organization–Environment framework and the theory of organizational readiness for change. Particular attention is given to Pakistan's experience with electronic immunization registries and digital health platforms as an existing foundation for future AI applications. The study finds that AI has considerable potential to strengthen immunization through identification of zero-dose and dropout-prone children, demand forecasting, geographic targeting, vaccine supply management, anomaly detection, and data-driven decision-making. However, technological availability alone is insufficient to generate sustained improvements in immunization performance. Organizational readiness—including leadership commitment, institutional

capacity, workforce competencies, interoperable infrastructure, data quality, governance mechanisms, and the ability of managers to act on analytical insights—emerges as the critical link between AI capability and program outcomes. The study therefore proposes an AI readiness framework for Pakistan's immunization system that integrates digital infrastructure, organizational readiness, workforce preparedness, data governance, analytical capability, and evidence-based management. It concludes that Pakistan should pursue a phased, human-centred and governance-oriented approach to AI adoption, building upon existing digital health investments rather than treating AI as a standalone technological intervention.

Keywords:
artificial intelligence, digital transformation, immunization, Pakistan, organizational readiness, electronic immunization registry, data-driven decision-making, public health, Expanded Programme on Immunization

INTRODUCTION

Immunization is widely recognized as one of the most effective public health interventions for preventing infectious diseases, reducing childhood mortality, and improving population health (Andre et al., 2008; WHO, 2021). The global expansion of vaccination programs has generated substantial reductions in deaths and disease burden, but the benefits of immunization remain unevenly distributed across countries and population groups. The challenge is particularly pronounced in low- and middle-income countries, where immunization programs frequently operate under constraints involving health infrastructure, financing, human resources, geographical accessibility, information systems, and community-level barriers (Sato, 2018; Zarekar et al., 2025). Consequently, improving vaccination performance requires not only vaccines and service delivery capacity but also effective information systems capable of identifying eligible populations, monitoring vaccination histories, detecting missed doses, and supporting timely managerial action (Labrique et al., 2013; WHO, 2021).

The increasing importance of information and communication technologies has transformed the way health systems collect, manage, and use information. Digital health encompasses a broad range of technologies, including electronic health records, mobile health applications, electronic registries, telehealth, decision-support systems, data dashboards, geographic information systems, and increasingly artificial intelligence (WHO, 2021). The WHO's Global Strategy on Digital Health emphasizes that digital transformation should strengthen health systems rather than simply introduce isolated technological products. The updated strategy, extended through 2027, emphasizes the integration of financial, organizational, human, and technological resources and recognizes digital health as a mechanism for improving equitable, sustainable, and people-centered health systems (WHO, 2025). Thus, digital transformation should be understood as a process of changing how health systems operate and use information rather than merely replacing paper records with electronic ones.

Immunization programs are particularly suitable for digital transformation because they generate large quantities of longitudinal information. A single child's immunization history may include demographic information, birth information, vaccination dates, antigen-specific records, facility visits, missed appointments, outreach encounters, and follow-up activities. When such information is recorded electronically and linked appropriately, it can provide a longitudinal picture of vaccination behavior. Electronic immunization registries can therefore support individual-level tracking, defaulter identification, reminders, coverage monitoring, and program planning (Glanz et al., 2017; Mechael et al., 2024). The value of such systems is not simply that information becomes digital; rather, digital records can make

information more timely, accessible, and actionable.

The potential contribution of artificial intelligence is located at the next stage of this transformation. Traditional digital systems primarily enable the recording, retrieval, visualization, and communication of information. AI systems can potentially analyze large and complex datasets to identify patterns, estimate risk, make predictions, classify populations, optimize resource allocation, and support decisions (Topol, 2019; WHO, 2021). In immunization, this could include identifying children at high risk of vaccination dropout, predicting geographical areas with high concentrations of zero-dose children, forecasting vaccine demand, detecting unusual reporting patterns, or identifying facilities requiring additional supervision. AI therefore has the potential to shift immunization management from predominantly retrospective monitoring toward more predictive and proactive management.

However, AI should not be equated with digitalization. AI depends on digital infrastructure, but digital infrastructure alone does not guarantee effective AI. Algorithms require data that are sufficiently complete, accurate, representative, timely, interoperable, and appropriately governed (Kraus et al., 2024; WHO, 2021). If health records are fragmented or inaccurate, AI may produce unreliable outputs. Similarly, if managers lack the authority, resources, or skills to respond to AI-generated alerts, predictive capability may have little effect on actual service delivery. The organizational environment is therefore as important as the technology itself (Weiner, 2009; Li et al., 2025).

Pakistan provides an important context for examining this relationship. The country has experienced considerable improvement in routine immunization coverage over the past decade. WHO and UNICEF estimates indicate that DTP3 coverage increased from 64% in 2012 to 86% in 2023. The country subsequently achieved 87% DTP3 coverage in 2024, described by UNICEF as Pakistan's highest-ever DTP3 coverage (UNICEF, 2025; WHO & UNICEF, 2024). This progress demonstrates the capacity of the immunization system to improve coverage. Nevertheless, aggregate national coverage can conceal substantial inequalities and missed populations.

The continuing presence of zero-dose and under-immunized children demonstrates this problem. Pakistan's 2023 estimates included approximately 396,000 zero-dose children and approximately 925,000 children who had not received DTP3 (UNICEF Pakistan, 2024). These categories represent different operational challenges. Zero-dose children may be completely outside the routine immunization system, whereas children who received earlier doses but failed to complete the schedule may be experiencing barriers related to follow-up, caregiver engagement, service accessibility, mobility, or health-system continuity. Identifying these groups requires individual-level or sufficiently granular information that can be analyzed rapidly and translated into targeted action.

Pakistan's experience with digital immunization provides a foundation for this transformation. One of the most significant examples is the Zindagi Mehfooz (ZM) electronic immunization registry. The ZM platform combines a smartphone application for vaccinators, web-based dashboards for supervisors and managers, SMS alerts and reminders for caregivers, a call center, child registration, immunization tracking, and data-use functions (Mechael et al., 2024). Its development illustrates the movement from paper-based reporting toward digitally enabled monitoring and follow-up.

The evaluation of Zindagi Mehfooz is particularly important because it provides evidence from the Pakistani health-system context rather than simply transferring findings from other countries. Mechael et al. (2024) found that the registry improved the availability and use of immunization data and was positively received by multiple groups within the immunization system. The intervention was also associated with improvements in several vaccination indicators, although the researchers appropriately emphasized that these changes could not be attributed to ZM alone because it operated alongside other immunization-strengthening interventions. The evaluation also identified

implementation barriers, including the continued burden of paper and digital reporting and differences in system use across settings.

This experience provides an important lesson for AI-enabled transformation. The transition from digital registration to AI-enabled decision support should not be understood as simply adding algorithms to an existing application. Instead, it represents a broader institutional transformation in which digital data must become sufficiently reliable and usable to support predictive analytics and operational decisions. This can be expressed as:

Digital infrastructure → quality data → analytical capability → actionable intelligence → organizational action → improved immunization performance.

Organizational readiness operates throughout this pathway.

The concept of organizational readiness is particularly relevant because healthcare technologies are implemented within existing organizational structures, workflows, professional roles, and institutional cultures. Weiner (2009) conceptualizes organizational readiness as a shared state of commitment and collective efficacy for implementing change. In other words, organizations are not ready merely because a technology is technically available; they must also believe in the value of the change and possess the capacity to implement it. Shea et al. (2014) similarly demonstrate the importance of measuring organizational readiness as a multidimensional implementation condition.

The Technology–Organization–Environment framework provides a complementary perspective. Tornatzky and Fleischer (1990) argue that technological adoption is shaped by technological characteristics, organizational conditions, and the external environment. Later research has applied TOE to digital health and AI adoption, emphasizing technological infrastructure, organizational capability, leadership, resources, regulatory arrangements, and external pressures (Kraus et al., 2024). Kraus et al. (2024), for example, identify technological, macroeconomic, regulatory, organizational, and user-specific readiness as important dimensions influencing AI adoption in healthcare institutions.

Recent evidence from Pakistan reinforces the importance of organizational factors. Li et al. (2025) examined digital transformation in Pakistan's public healthcare organizations using the TOE framework and found that transformational leadership positively influenced employee commitment to digital transformation, which in turn contributed to organizational digital maturity. Their analysis further indicated that AI readiness strengthened the relationship between employee commitment and organizational digital maturity. These findings are highly relevant to immunization because EPI transformation involves not only technological infrastructure but also leadership, workforce engagement, and institutional capacity.

Data-driven decision-making is another critical dimension. Health information systems are valuable only when the information they generate is used to guide decisions (Nutley & Reynolds, 2013). In immunization, data can inform microplanning, outreach targeting, supervision, vaccine distribution, defaulter tracing, and performance monitoring. The WHO's 2025 strategy for optimizing routine health information systems emphasizes integrated, interoperable, evidence-informed, and aligned information systems as foundations for better service management and monitoring (WHO, 2025). Therefore, AI should be viewed as an extension of data-driven management rather than as a substitute for sound health information systems.

International evidence supports the potential of digital technologies to improve immunization. Zarekar et al. (2025) conducted a systematic review and meta-analysis of ICT interventions in LMIC immunization programs, including 27 studies involving 354,979 children. Almost all included studies reported positive effects in at least one area of immunization performance, including coverage, timeliness, record quality, vaccine stock management, or cold-chain-related functions. The meta-analysis found that reminder interventions increased the odds of receiving the third

pentavalent dose and being fully immunized by one year, although substantial heterogeneity existed across studies. This evidence supports the broader proposition that digital interventions can contribute to immunization performance, while simultaneously demonstrating the importance of context and implementation quality.

The present study therefore approaches AI-enabled immunization transformation as a system-level organizational and technological change, rather than as a stand-alone innovation. The central argument is that AI can improve immunization performance indirectly by improving the speed, accuracy, targeting, and predictive capacity of information systems. However, the magnitude of this contribution depends on organizational readiness, workforce capacity, data quality, interoperability, governance, and institutional ability to convert predictions into action.

The study addresses four objectives. First, it examines Pakistan's existing digital transformation trajectory in immunization. Second, it analyzes the technological and organizational conditions required for AI-enabled transformation. Third, it identifies potential AI applications for improving immunization planning, targeting, monitoring, and performance. Fourth, it develops a conceptual AI readiness framework for Pakistan's immunization program.

The article makes three principal contributions. First, it connects Pakistan-specific digital immunization evidence with the wider literature on AI and digital transformation. Second, it integrates TOE theory and organizational readiness theory to explain why technological availability alone does not guarantee implementation success. Third, it proposes a practical framework for assessing AI readiness while emphasizing human oversight, data governance, equity, and institutional sustainability.

2. Research Methodology

2.1 Research Design

This study adopts a qualitative secondary research design based on documentary analysis and thematic synthesis. No primary interviews, surveys, questionnaires, experiments, or field observations were undertaken. The empirical foundation consists exclusively of secondary sources, including peer-reviewed journal articles, systematic reviews, official WHO and UNICEF publications, policy documents, and documented evaluations of digital immunization interventions.

A qualitative design is appropriate because the study seeks to interpret relationships among technology, organizations, data, institutions, and program performance rather than statistically estimate a causal effect of AI. Qualitative document analysis is particularly appropriate for policy and health-system research because documentary evidence can reveal institutional structures, implementation processes, organizational barriers, governance requirements, and policy priorities that are not necessarily captured through quantitative indicators alone (Bowen, 2009).

The research therefore does not claim to measure the causal effect of AI on Pakistan's immunization coverage. Instead, it synthesizes existing evidence to determine how AI-enabled digital transformation could plausibly contribute to program performance and under what organizational conditions such transformation is likely to succeed.

2.2 Sources and Evidence Base

The evidence base was organized into five categories.

The first category consisted of peer-reviewed literature on digital health and immunization, including research on electronic immunization registries, mobile health, reminders, digital monitoring, and ICT-supported vaccination programs (Agarwal et al., 2016; Domek et al., 2016; Feroz et al., 2021; Zarekar et al., 2025).

The second category consisted of Pakistan-specific digital immunization evidence, particularly research evaluating the Zindagi Mehfooz electronic immunization registry (Chandir et al., 2018; Mechael et al., 2024).

The third category consisted of AI and digital transformation literature, including research

examining AI adoption, organizational readiness, digital maturity, and implementation factors in healthcare (Kraus et al., 2024; Li et al., 2025).

The fourth category consisted of international policy and governance documents, particularly WHO publications concerning digital health, AI ethics, health information systems, and responsible innovation (WHO, 2021, 2025).

The fifth category consisted of official immunization statistics and reports, particularly WHO and UNICEF estimates of immunization coverage and Pakistan-specific information concerning zero-dose and under-immunized children (UNICEF Pakistan, 2024; UNICEF, 2025; WHO & UNICEF, 2024).

2.3 Analytical Framework

The analysis combines the TOE framework with organizational readiness theory. The TOE framework identifies three broad dimensions of technological adoption: technology, organization, and environment (Tornatzky & Fleischer, 1990). The organizational readiness perspective complements TOE by explaining the willingness and collective capacity of organizations to implement change (Weiner, 2009).

For the purposes of this study, the framework was operationalized through five analytical dimensions:

1. technological readiness;
2. organizational readiness;
3. workforce readiness;
4. data and governance readiness; and
5. environmental readiness.

These dimensions were then examined in relation to AI capability and immunization performance.

2.4 Thematic Analysis

The documentary material was analyzed thematically. The initial themes were developed deductively from the research objectives and theoretical framework. These included digital infrastructure, organizational leadership, workforce capability, data quality, interoperability, data-driven decision-making, AI applications, governance, equity, and immunization performance.

Additional themes were identified inductively during the synthesis. These included parallel reporting burdens, variation in technology adoption, rural–urban differences, caregiver engagement, predictive targeting, and the distinction between technological capability and actual organizational use.

The analysis focused particularly on the mechanisms through which digital information can affect program performance. For example, an electronic registry can improve record availability; improved records can facilitate defaulter identification; defaulter identification can enable targeted follow-up; and targeted follow-up can potentially improve completion rates. AI could extend this pathway by predicting which children or locations are most likely to experience missed vaccination.

2.5 Trustworthiness

Triangulation was used to improve analytical credibility. Empirical claims were preferentially supported by peer-reviewed studies or official international datasets, while theoretical arguments were grounded in established implementation and technology-adoption literature. Pakistan-specific conclusions were supported by Pakistan-specific evidence wherever available.

The study also distinguishes between established evidence, emerging evidence, and proposed applications. This distinction is particularly important for AI because the evidence base concerning nationwide AI-enabled routine immunization in Pakistan remains limited. Accordingly, potential AI applications are not presented as established nationwide outcomes.

3. Pakistan's Immunization Context: Why Digital Transformation Matters

Pakistan has made considerable progress in routine immunization. DTP3 coverage increased from 64% in 2012 to 86% in 2023 and reached 87% in 2024 (UNICEF, 2025; WHO & UNICEF, 2024). This improvement reflects sustained efforts by the national and provincial EPI programs, health workers, international partners, and communities.

Table 1 Pakistan's DTP3 Coverage, 2012–2024

Year	DTP3 coverage (%)
2012	64
2013	65
2014	69
2015	72
2016	75
2017	75
2018	80
2019	84
2020	80
2021	83
2022	85
2023	86
2024	87

Note. Who/Unicef estimates for 2012–2023 are reported in the WHO Pakistan immunization country profile. The 2024 estimate of 87% was reported by UNICEF as Pakistan's highest-ever DTP3 coverage (UNICEF, 2025; WHO & UNICEF, 2024).

Despite this progress, national averages conceal important gaps. Pakistan's 2023 estimates included approximately 396,000 zero-dose children and approximately 925,000 children who had not received DTP3 (UNICEF Pakistan, 2024). These figures illustrate why the next phase of immunization improvement requires better identification and targeting.

Table 2 Selected Immunization Gaps in Pakistan

Indicator	Estimated value
DTP3 coverage, 2023	86%
DTP3 coverage, 2024	87%
Zero-dose children, 2023	~396,000
Children without DTP3, 2023	~925,000

Note. Values Are Based On Who/Unicef Estimates And Unicef Pakistan's 2023 Wuenic Reporting (Unicef Pakistan, 2024; Who & Unicef, 2024).

The existence of zero-dose children raises a fundamental information problem: health managers need to know not simply how many children are missed but where they are, which communities they belong to, and what barriers prevent them from receiving vaccines. Similarly, dropout requires information about individual vaccination histories and the timing of previous doses.

Digital health systems can address these information requirements by enabling individual-level registration and longitudinal tracking (Labrique et al., 2013; WHO, 2021). The transition from aggregate reporting toward case-based digital information is therefore strategically important.

4. From Digitization to AI-Enabled Transformation: The Zindagi Mehfooz Experience

The Zindagi Mehfooz electronic immunization registry represents one of Pakistan's most important digital immunization initiatives. The system includes a smartphone application for vaccinators, web-based dashboards for managers and supervisors, SMS reminders, a call center, individual child registration, vaccination tracking, and data-use functions (Mechael et al., 2024).

Electronic immunization registries are designed to improve the collection, management, analysis, and use of individual-level vaccination information (Glanz et al., 2017; Mechael et al., 2024). Their potential value lies in connecting individual vaccination histories with operational functions such as reminders, defaulter lists, monitoring, and microplanning.

The evaluation by Mechael et al. (2024) found that ZM improved data availability and use and was viewed positively by administrators, supervisors, vaccinators, and caregivers. The system was also associated with improvements in selected immunization outcomes. However, the authors emphasized that ZM operated as one component within a broader package of immunization interventions and therefore did not permit simple attribution of outcome improvements to the registry alone.

The evaluation also revealed implementation challenges. Dual paper and digital reporting created additional workload, while differences in system use existed across locations. These findings are highly significant for AI adoption because AI depends on consistent digital data.

The broader lesson is that **digital transformation is an organizational process**. The technology may be sophisticated, but its contribution depends on whether health workers actually use it, whether data are complete, and whether managers use the resulting information to guide decisions.

5. Organizational Readiness as the Core Condition for AI Adoption

Organizational readiness is central to digital transformation because technologies are implemented through organizations rather than in isolation (Weiner, 2009). A health department may possess sophisticated software but remain poorly prepared to use it if staff lack training, leaders do not support the technology, workflows are incompatible, or financing is inadequate.

Weiner's (2009) theory emphasizes two central dimensions: organizational commitment to change and organizational efficacy. Members must collectively value the change and believe that the organization has the ability to implement it. Shea et al. (2014) similarly conceptualized organizational readiness as a measurable implementation condition.

The TOE framework reinforces this argument by positioning organizational characteristics alongside technology and environmental conditions (Tornatzky & Fleischer, 1990). In AI adoption, organizational factors include leadership, organizational culture, resources, workflow integration, communication, staff skills, and managerial support (Kraus et al., 2024).

The Pakistan-specific evidence of Li et al. (2025) is particularly relevant. Their study of public healthcare organizations found that digital transformational leadership positively affected employee commitment to digital transformation, while employee commitment contributed to organizational digital maturity. AI readiness further influenced this transformation pathway.

This suggests that EPI leadership should treat AI not simply as an information technology project but as an institutional transformation program. Leaders must establish priorities, allocate resources, ensure training, reduce unnecessary reporting duplication, create accountability mechanisms, and establish trust in digital systems.

6. Technological Readiness, Interoperability, and Infrastructure

Technological readiness involves more than possessing computers or smartphones. It includes connectivity, software architecture, interoperability, data standards, cybersecurity, storage capacity, technical support, and analytical infrastructure (WHO, 2021, 2025).

Interoperability is particularly important. If vaccination data are maintained in disconnected systems, AI models cannot easily integrate information across platforms. A child-level record may need to be connected with geographic data, facility information, vaccination history, outreach activities, and population information.

WHO's strategy for optimizing routine health information systems emphasizes integrated and interoperable systems capable of supporting evidence-informed health service management (WHO, 2025). This principle is directly relevant to Pakistan's immunization program.

The experience of Zindagi Mehfooz illustrates the importance of this infrastructure. The system's mobile and dashboard components enable individual-level information to move from frontline vaccination activities toward managerial monitoring. However, persistent parallel paper reporting illustrates how legacy processes can weaken digital transformation (Mechael et al., 2024).

Therefore, Pakistan's AI strategy should begin with strengthening the digital foundation rather than immediately introducing complex algorithms.

7. Data Quality and Data-Driven Decision-Making

Data quality is the foundation of AI-enabled public health. AI models cannot produce reliable predictions from unreliable information. Data quality includes completeness, accuracy, timeliness, consistency, validity, and representativeness (WHO, 2025).

A distinction must therefore be made between data availability and data usability. A database containing millions of records may remain unsuitable for AI if records are duplicated, essential variables are missing, geographical identifiers are inconsistent, or vaccination events are entered after long delays.

The Zindagi Mehfooz experience demonstrates the value of transforming data into operational information. Defaulter lists were particularly important because they translated vaccination records into actionable follow-up tasks (Mechael et al., 2024).

AI can extend this process from descriptive to predictive management. A conventional digital system can identify a child who has already missed a scheduled vaccine. An AI model could potentially identify a child who is likely to miss the next dose. This distinction creates an opportunity for earlier intervention.

However, predictive accuracy must be accompanied by interpretability. Managers need to understand why a child or community has been classified as high risk. Otherwise, predictions may not translate into action.

8. Potential Applications of AI in Pakistan's Immunization Program

8.1 Identification of Zero-Dose Children

AI-supported geographic and demographic analysis could help identify areas where zero-dose children are concentrated. Models could potentially combine historical vaccination coverage, facility accessibility, population characteristics, geographic information, and service utilization patterns.

Recent literature specifically examining AI and routine immunization suggests that AI can support identification of zero-dose populations, optimization of vaccine delivery, and data-driven decision-making (e.g., recent narrative evidence on AI and zero-dose children). However, such applications should be treated as decision-support tools rather than replacements for community-level knowledge.

8.2 Prediction of Vaccination Dropout

Predictive analytics may be especially useful for identifying children at risk of failing to complete their vaccination schedules. Digital immunization registries provide the longitudinal records needed for such models.

The ZM platform demonstrates movement in this direction through its digital tracking and predictive functionality (Mechael et al., 2024). A predictive model could potentially classify children according to risk and allow health workers to prioritize follow-up.

8.3 Vaccine Demand Forecasting

AI could analyze historical vaccination data, birth estimates, facility utilization, seasonal patterns, and campaign schedules to forecast vaccine requirements. Better forecasting could reduce stockouts and improve resource allocation (Zarekar et al., 2025).

8.4 Geographic Targeting

Geographic information systems combined with machine learning could identify geographic clusters of low coverage. This would allow EPI managers to prioritize outreach activities in areas where the expected marginal benefit is greatest.

8.5 Anomaly Detection

AI could identify unusual reporting patterns, such as sudden declines in vaccination activity, implausibly high reporting values, delayed reporting, or unusual facility-level variations. Such systems could assist supervisors in identifying locations requiring verification.

8.6 Intelligent Caregiver Communication

AI-supported conversational systems could provide basic information concerning vaccination schedules, appointment reminders, and frequently asked questions. However, complex clinical questions and adverse-event concerns should be referred to trained health professionals. Human oversight remains essential (WHO, 2021).

Table 3 Potential AI Applications and Expected Contributions to Immunization Performance

AI application	Data required	Potential benefit	Performance indicator
Zero-dose prediction	Coverage, geographic and demographic data	Targeted outreach	Reduction in zero-dose children
Dropout prediction	Individual vaccination histories	Early follow-up	Reduced dropout
Demand forecasting	Historical utilization and population estimates	Improved vaccine planning	Reduced stockouts
Geographic targeting	GIS and coverage data	Prioritized outreach	Improved equity
Anomaly detection	Facility-level reporting	Faster verification	Improved data quality
Caregiver chatbot	Schedule and information data	Improved communication	Improved engagement
Workforce analytics	Vaccinator activity	Improved supervision	Higher reporting compliance
Campaign planning	Population and historical campaign data	Better resource allocation	Improved campaign performance

Note. These are potential applications. The table does not imply that all functions are currently implemented nationwide in Pakistan.

9. Evidence Linking Digital Technologies to Immunization Performance

The strongest empirical evidence currently available concerns digital health and ICT rather than AI specifically. This distinction is important. Zarekar et al. (2025) reviewed 6,535 records and included 27 studies involving 354,979 children. Almost all included studies found positive effects of ICT interventions on at least one immunization-related outcome. Their meta-analysis found that reminder interventions increased the odds of receiving the third pentavalent dose (OR = 2.32, 95% CI [1.34, 4.03]) and being fully immunized at one year (OR = 2.61, 95% CI [1.20, 5.67]). However, heterogeneity was high, with I^2 values of 82% and 89%, respectively. Earlier evidence also supports the value of mobile interventions. Systematic reviews have reported that mobile-phone-based interventions can improve vaccination uptake, completeness, and

timeliness in LMICs (Bangure et al., 2015; Eze et al., 2021). Domek et al. (2016) also demonstrated the potential of mobile technology to support childhood immunization in Guatemala, while Stockwell et al. (2017) found that text-message interventions could improve immunization outcomes.

These findings suggest that digital interventions can influence immunization performance through several pathways: reminders improve caregiver compliance; electronic records improve tracking; dashboards improve supervision; and digital communication improves information flow.

AI potentially adds another layer by enabling prediction and prioritization. However, the evidence should not be overstated. There is currently stronger evidence that digital health improves immunization management than that AI independently improves national immunization coverage. This distinction is essential for a methodologically defensible argument.

10. Workforce Readiness and Human–AI Collaboration

Technology is ultimately implemented by people. Workforce readiness therefore represents one of the most important dimensions of AI adoption (Kraus et al., 2024; Li et al., 2025).

Frontline vaccinators do not need to become data scientists. Instead, they need sufficient digital literacy to enter accurate data, interpret alerts, understand system limitations, and communicate with supervisors. Managers require somewhat different capabilities: they need to interpret dashboards, evaluate predictive outputs, allocate resources, and determine whether an AI recommendation is operationally appropriate.

This supports a human-in-the-loop model in which algorithms provide analytical assistance while professionals retain responsibility for decisions. WHO emphasizes human autonomy, accountability, transparency, safety, equity, and responsibility in AI-enabled health systems (WHO, 2021).

Training should therefore include not only technical operation but also data interpretation, privacy, cybersecurity, bias awareness, and understanding of algorithmic uncertainty.

11. Data Governance, Privacy, Equity, and Ethical Risks

AI-enabled immunization systems may process sensitive information about children, families, vaccination histories, locations, and healthcare utilization. Strong data governance is consequently essential.

WHO's AI ethics framework identifies six major principles: protection of human autonomy; promotion of human well-being and safety; transparency and explainability; responsibility and accountability; inclusiveness and equity; and sustainable and responsive AI (WHO, 2021).

These principles are directly relevant to Pakistan's immunization program. An algorithm should not systematically disadvantage communities because their historical data are incomplete. For example, remote communities may have fewer digital records precisely because they are underserved. A model trained on existing records could therefore incorrectly interpret low data availability as low vaccination need.

This creates a significant ethical concern: algorithmic invisibility can reproduce social invisibility.

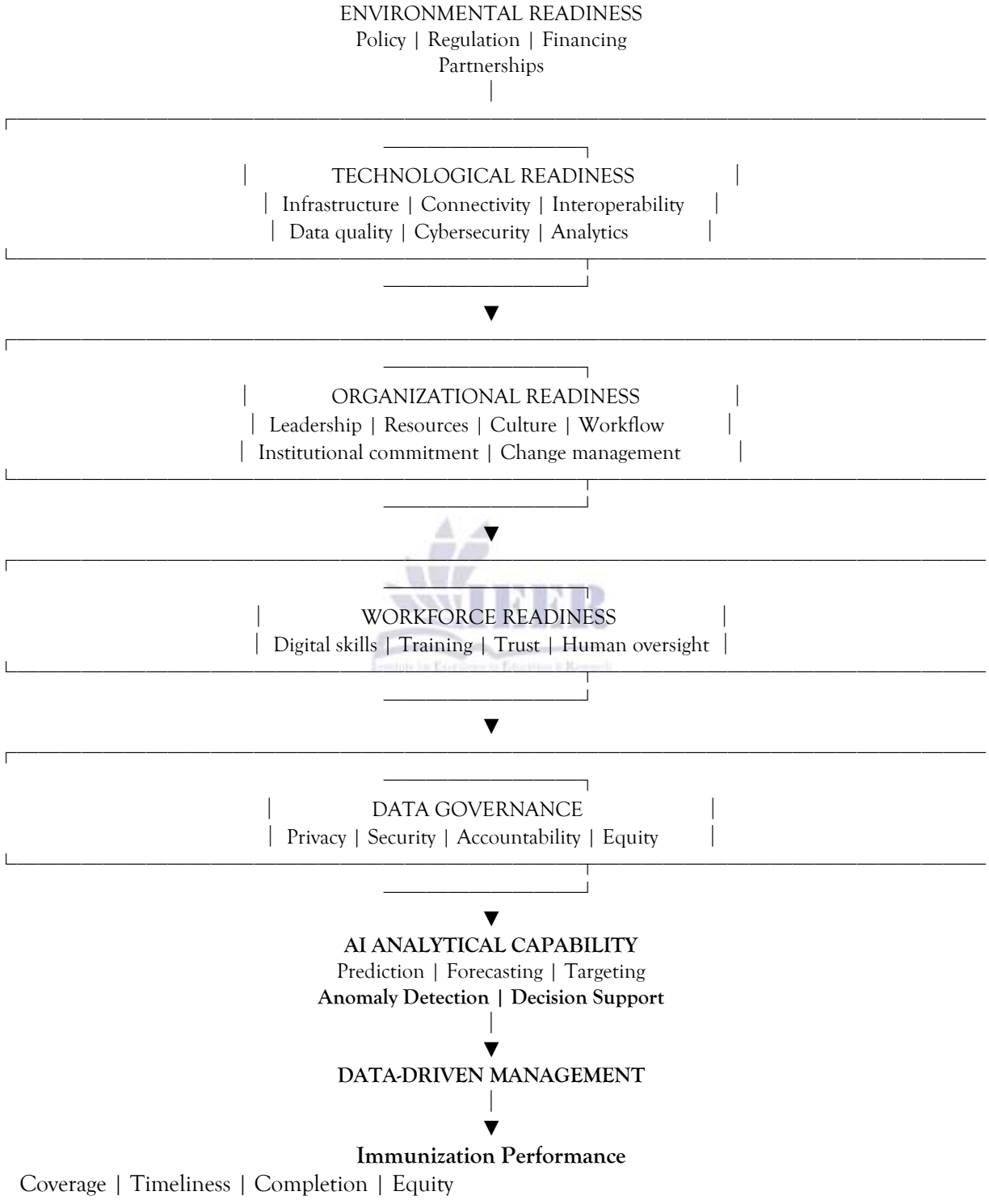
Equity therefore needs to be incorporated into model development and evaluation. AI systems should be assessed across provinces, rural and urban populations, socioeconomic groups, and other relevant population categories.

Data governance must also specify who can access information, how long data are retained, how information is protected, and who is accountable when algorithmic decisions cause harm. WHO's health information system governance guidance emphasizes that effective governance is a prerequisite for reliable health information systems (WHO, 2021).

12. Proposed AI Readiness Framework for Pakistan's Immunization Program

Figure 1

Proposed AI Readiness Framework



The proposed framework combines the technological, organizational, and environmental dimensions of TOE with organizational readiness and data-governance requirements (Tornatzky & Fleischer, 1990; Weiner, 2009; WHO, 2021).

Technological readiness ensures that the health system can collect, store, integrate, and process information. Organizational readiness ensures that institutions can incorporate AI into workflows. Workforce readiness ensures that people can operate and critically interpret AI systems. Data governance protects privacy, security, accountability, and equity. Environmental readiness encompasses policy, financing, regulation, partnerships, and broader health-system conditions.

The framework therefore conceptualizes AI readiness as multidimensional and sequential but also interdependent. Weakness in any major dimension can undermine the effectiveness of the entire system.

13. Discussion

The evidence synthesized in this study indicates that Pakistan is already moving toward the digital foundations required for more advanced analytical systems. The Zindagi Mehfooz experience demonstrates that individual-level digital registration, reminders, dashboards, and follow-up mechanisms can strengthen the availability and use of immunization information (Mechael et al., 2024). More recent national digital-transformation initiatives also indicate continued movement toward electronic immunization information systems and real-time monitoring. WHO documentation on Pakistan's digital EPI transformation reports expansion of a National Electronic Immunization Registry across districts and vaccination centres, illustrating the increasing institutionalization of digital reporting.

The critical issue is therefore not whether Pakistan should digitize immunization but how it should progress from digitization toward intelligent data use.

The first major finding is that digital transformation should precede large-scale AI deployment. AI requires reliable digital data. Without strong data architecture, interoperability, and governance, algorithms may generate misleading outputs.

The second finding is that organizational readiness is the bridge between technology and performance. Evidence from Pakistan's public healthcare sector indicates that leadership and employee commitment influence digital maturity and that AI readiness is part of this transformation process (Li et al., 2025).

The third finding concerns data-driven management. The value of an immunization database lies in the decisions that it enables. A defaulter list is valuable because it allows a vaccinator to act. A predictive model is valuable only if its output results in an appropriate intervention.

The fourth finding is that AI's most promising contribution may be prioritization rather than automation. Pakistan's immunization program operates across a large and heterogeneous population. Managers cannot manually examine every record or geographic location. AI can potentially help identify where limited resources should be directed first.

The fifth finding concerns the relationship between prediction and equity. Predictive models can unintentionally reinforce existing inequalities if they are trained on biased data. Therefore, the communities with the weakest historical data may require additional safeguards rather than lower priority.

Finally, the evidence demonstrates that technological innovation should be evaluated in terms of implementation rather than novelty. WHO's digital-health strategy explicitly emphasizes country needs and warns against the assumption that technologies will automatically be adopted simply because they are available (WHO, 2021, 2025).

14. Policy and Managerial Implications

The findings generate several policy implications.

First, Pakistan should prioritize data quality and interoperability before expanding advanced AI. National and provincial immunization authorities should establish common standards for

identifiers, reporting fields, geographic coding, and data exchange.

Second, unnecessary parallel paper and electronic reporting should be reduced. The ZM experience demonstrates that duplicate reporting can create workload and reduce digital adoption (Mechael et al., 2024).

Third, AI readiness should become part of workforce development. Training should address digital literacy, data interpretation, algorithmic limitations, privacy, and cybersecurity.

Fourth, AI should initially be deployed for clearly defined operational problems. Predictive dropout identification, zero-dose mapping, vaccine demand forecasting, and anomaly detection are more directly connected to immunization management than generalized AI applications.

Fifth, AI systems should undergo independent evaluation. Evaluation should examine technical performance as well as coverage, timeliness, equity, cost, workload, user acceptance, and unintended consequences.

Sixth, governance mechanisms should be established before deployment. These should define responsibility for algorithmic decisions, data access, privacy protection, model validation, monitoring, and redress mechanisms (WHO, 2021).

Table 4 Suggested Indicators for Evaluating AI-Enabled Immunization Transformation

Dimension	Indicator
Coverage	DTP3 and full immunization coverage
Equity	Coverage gap between high- and low-performing areas
Zero-dose	Number/proportion of zero-dose children
Dropout	DTP1–DTP3 dropout
Timeliness	Vaccination within recommended schedule
Data quality	Completeness, accuracy, timeliness
Adoption	Active use by facilities and vaccinators
Workforce	Staff trained and competent
AI performance	Sensitivity, specificity, calibration
Governance	Privacy and accountability mechanisms
Efficiency	Reporting and follow-up time
Sustainability	Recurrent financial and technical requirements

Note. The indicators are proposed by the authors based on the qualitative synthesis of the literature and secondary evidence examined in this study. They are intended to assess organizational readiness, technological capacity, data quality, workforce preparedness, governance, AI capability, data-driven management, and immunization program performance. The indicators are not intended to represent an existing standardized national measurement framework.

15. Limitations

This study has several limitations. First, it is entirely based on secondary evidence and therefore does not provide original primary empirical data. The study should be interpreted as a qualitative analytical synthesis rather than a causal evaluation of AI.

Second, the Pakistan-specific literature concerning AI-enabled routine immunization remains relatively limited. Much of the available evidence concerns digital health, electronic registries, mobile interventions, and data systems rather than mature AI implementation. Consequently, several AI applications discussed in the article represent future opportunities rather than established nationwide practices.

Third, international digital-health evidence may not be directly transferable to Pakistan because implementation conditions vary across countries. Differences in infrastructure, health financing, governance, workforce capacity, digital literacy,

and socioeconomic conditions can influence intervention effectiveness (Zarekar et al., 2025).

Fourth, national vaccination coverage cannot be attributed to digital transformation alone. Immunization performance is influenced by vaccine availability, financing, political commitment, workforce, outreach, community engagement, security, geography, and socioeconomic conditions. The ZM evaluation itself cautioned against attributing observed improvements solely to the digital intervention (Mechael et al., 2024).

16. Future Research

Future research should move from conceptual analysis toward empirical evaluation of AI readiness and implementation.

First, researchers should develop and validate a Pakistan-specific AI readiness assessment instrument covering technological, organizational, workforce, governance, and environmental dimensions.

Second, implementation research should examine how AI-generated recommendations influence district managers and vaccinators. It is important to determine whether predictive alerts actually result in earlier outreach and reduced dropout.

Third, prospective evaluations should assess whether AI-supported management produces measurable improvements in vaccination coverage, timeliness, equity, and efficiency.

Fourth, algorithmic fairness should receive particular attention. Models should be evaluated across provinces, rural and urban settings, socioeconomic groups, and populations with different levels of digital representation.

Fifth, cost-effectiveness research is necessary. AI systems involve development, maintenance, training, infrastructure, data governance, and cybersecurity costs. These costs must be weighed against measurable improvements in health-system performance.

Finally, sustainability should be investigated. A successful pilot may fail if it depends excessively on external financing or technical expertise. Long-term success requires institutional ownership, domestic financing, workforce development, and integration into national health-information architecture.

17. Conclusion

Artificial intelligence–enabled digital transformation has significant potential to strengthen Pakistan's immunization program, but its effectiveness will depend less on the availability of AI technologies than on the readiness of the institutions expected to adopt and use them. The analysis demonstrates that Pakistan has already developed important foundations for digital transformation through electronic immunization registries, digital reporting systems, mobile technologies, geospatial information, electronic records, and data-based monitoring mechanisms. These developments provide a practical foundation upon which more advanced AI capabilities can gradually be developed.

The study finds that AI can contribute to immunization performance by transforming large volumes of routine health data into actionable intelligence. Predictive identification of zero-dose and dropout-prone children, geographic targeting, vaccine demand forecasting, supply-chain monitoring, anomaly detection, automated reporting, and intelligent communication with caregivers represent promising areas for future application. However, these possibilities should not be interpreted as evidence that AI alone will solve Pakistan's immunization challenges. AI systems are only as effective as the data, institutions, infrastructure, and human decision-making processes that support them.

Organizational readiness therefore emerges as the central condition connecting AI adoption with program performance. Leadership commitment, adequate financial and technical resources, trained personnel, supportive organizational cultures, interoperable information systems, clearly defined workflows, and the capacity to translate analytical outputs into operational decisions are essential. Without these conditions, AI may increase technological complexity without producing meaningful improvements in vaccination coverage, timeliness, equity, or service efficiency. Organizational readiness should

consequently be treated as a continuous process rather than a one-time prerequisite for technology adoption.

The findings further indicate that data quality and interoperability are fundamental to any future AI strategy for immunization in Pakistan. Fragmented databases, incomplete records, duplicate reporting, inconsistent identifiers, limited interoperability, and parallel paper and digital systems can reduce the reliability of AI-generated predictions. Strengthening data standards, unique identifiers, interoperability, real-time reporting, data validation, and institutional data governance should therefore precede or accompany large-scale AI deployment. AI should be integrated into an existing data ecosystem that is sufficiently reliable to support responsible decision-making.

A human-centred approach is equally important. AI should support rather than replace vaccinators, supervisors, district managers, and policymakers. Local health workers possess contextual knowledge that automated systems cannot fully capture, particularly in areas affected by insecurity, mobility, social barriers, geographical isolation, or community distrust. The most appropriate model for Pakistan is therefore human–AI collaboration in which AI identifies patterns, risks, and priorities while health professionals interpret these outputs and make context-sensitive decisions.

The study consequently proposes a phased approach to AI-enabled immunization transformation. The first phase should strengthen digital infrastructure, data quality, interoperability, and governance. The second should develop organizational and workforce readiness through leadership support, training, technical capacity, and institutional change management. The third should introduce carefully selected AI applications in areas where reliable data and clear operational value already exist. These applications should initially be tested through controlled pilots and evaluated against clearly defined indicators before wider implementation. Continuous monitoring should assess not only technological performance but also equity, usability, accountability, privacy, and actual improvements in immunization services.

Overall, the central conclusion is that AI should be viewed as an institutional transformation process rather than simply a technological upgrade. Pakistan's immunization program does not need to begin its digital transformation from the beginning; rather, it can build on existing digital investments and gradually develop an AI-enabled ecosystem. Organizational readiness, data-driven management, workforce capacity, interoperability, responsible governance, and sustained institutional commitment will determine whether this transition produces meaningful program improvements. If these conditions are addressed systematically, AI can become a valuable decision-support capability for making Pakistan's immunization system more targeted, responsive, efficient, equitable, and resilient.

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