

Evidence-Driven AI Governance for Healthcare: A PEARL-PATHWAY Analysis of Madinah

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Abstract—The rapid integration of artificial intelligence (AI) into healthcare systems has intensified the need for governance frameworks that ensure safety, accountability, ethical, and sustainable deployment. However, existing AI governance approaches are primarily articulated through high-level ethical and regulatory principles, with limited operational guidance tailored to specific healthcare contexts. This challenge is particularly evident in dynamic settings such as AI Madinah, Saudi Arabia, where demographic diversity, evolving healthcare needs, and large-scale public health pressures, including the presence of millions of visitors annually during Hajj and Umrah, require adaptive and context-aware governance. This study presents an evidence-driven approach to AI governance analysis that directly links empirical healthcare needs with regulatory frameworks. It integrates the PEARL framework to systematically analyse an initial corpus of 4,277 healthcare publications related to Madinah, refined to 243 articles through inclusion and exclusion criteria, extracting structured representations of healthcare priorities, with the PATHWAY framework to evaluate alignment between these needs and both Saudi Arabian and international AI governance frameworks. This enables a systematic assessment of governance applicability, identification of gaps, and analysis of associated risks. The results reveal that while existing frameworks provide strong foundations in terms of privacy, ethics, and risk-based regulation, they lack operational pathways tailored to domain-specific healthcare requirements and local contexts. Key gaps are identified in areas including epidemiological surveillance, behavioural health, maternal and paediatric care, environmental health integration, and generative AI in public health communication. By bridging empirical evidence with governance analysis, this study advances a structured approach to domain-informed and context-sensitive AI governance. It contributes to the emerging field of computational policy analysis and provides evidence-driven insights for developing adaptive, scalable, and trustworthy AI governance strategies in healthcare systems.

Keywords—AI governance; healthcare AI; evidence-driven governance; PEARL framework; PATHWAY framework; governance gap analysis; domain-specific governance; context-aware governance; policy intelligence; sustainability

I. INTRODUCTION

The rapid expansion of artificial intelligence (AI) across healthcare systems is transforming how diseases are detected, managed, and prevented [1]. From predictive analytics for infectious disease outbreaks to decision-support systems for clinical diagnosis and personalised treatment, AI has become increasingly embedded within healthcare infrastructures

worldwide [2], [3], [4]. At the same time, this rapid integration has intensified concerns regarding safety, accountability, fairness, transparency, sustainability, and the protection of sensitive health data, prompting the emergence of a wide range of AI governance frameworks developed by national governments, international organisations, and regulatory bodies [5], [6]. Key examples include the European Union's AI Act [7], the United States Blueprint for an AI Bill of Rights [8] and Executive Order on AI [9], the United Kingdom's National AI Strategy [10], China's New Generation AI Development Plan (AIDP) [11], and Saudi Arabia's AI Ethics Principles [12]. See Table I for a list of Saudi and International AI governance instruments.

These governance efforts have largely been articulated through high-level principles, risk-based regulatory models, and ethical guidelines designed to ensure responsible AI deployment [13], [14]. While such frameworks provide important normative foundations and flexibility for gradual refinement over time, they remain abstract and insufficiently operationalized for the complex, context-specific realities of healthcare systems [15], [16]. In practice, healthcare environments are characterised by heterogeneous data types, population-specific risks, evolving epidemiological patterns, and deeply embedded socio-cultural factors, all of which require governance approaches that are not only principled but also operational, adaptive, and context-aware [17], [18].

This challenge becomes particularly pronounced in dynamic and high-pressure healthcare environments such as Madinah, Saudi Arabia. As a city with a rapidly evolving healthcare ecosystem, significant demographic diversity, and unique public health pressures associated with large-scale religious gatherings such as Hajj and Umrah, Madinah represents a complex and meaningful setting for examining the interplay between healthcare needs and AI governance [19], [20]. For instance, Official GASTAT statistics indicate that 10.97 million pilgrims performed Umrah in Q3 2025, reflecting sustained high demand and suggesting that annual volumes are likely to exceed the Vision 2030 target of 30 million annual pilgrims, thereby highlighting a shift toward large-scale operational governance [27]. These conditions create distinctive requirements for continuous surveillance [22], scalable healthcare delivery [23], behavioural health interventions [24], environmental monitoring [25], and digital health integration [26], making the region not merely a case study but a real-world empirical testbed for governance analysis.

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TABLE I. PUBLIC HEALTH (MADINAH): RELEVANT AI GOVERNANCE REGULATIONS, FRAMEWORKS AND POLICIES

Jurisdictions	Regulations / Frameworks / Policies	Citation
Saudi Arabia	Personal Data Protection Law (PDPL)	[32]
	AI Ethics Principles	[12]
	Generative Artificial Intelligence Guidelines for Government	[33]
	Human-Centered AI	[34]
	Saudi Food and Drug Authority (SFDA) Guidance for Artificial Intelligence and Machine Learning (AI/ML)-Enabled Medical Devices	[35]
	National Digital Government Strategy	[36]
International	EU AI Act	[7]
	EU Medical Device Regulation (MDR)	[37]
	EU In Vitro Diagnostic Regulation (IVDR)	[38]
	EU General Data Protection Regulation (GDPR)	[39]
	EU NIS2 Directive	[40]
	The European Green Deal	[41]
	UK National AI Strategy	[10]
	UK General Data Protection Regulation (UK GDPR)	[42]
	UK's Regulatory Sandbox	[43]
	US Blueprint for an AI Bill of Rights	[8]
	US Executive Order on AI	[9]
	US FDA Software as a Medical Device (SaMD) Framework	[44]
	NIST AI Risk Management Framework (AI RMF)	[45]
	Japan's AI Strategy	[46]
	Japan's Act on the Protection of Personal Information (APPI)	[47]
	Canada's AI Strategy for the Federal Public Service	[48]
	Canada's Personal Information Protection and Electronic Documents Act (PIPEDA)	[49]
	China's New Generation AI Development Plan (AIDP)	[11]
	China's Generative AI Regulation	[50]
Singapore's Regulatory Guidelines for Software Medical Devices	[51]	
Institutional	UNESCO Recommendation on the Ethics of AI	[52]
	WHO Guidance on AI in Healthcare	[28]
	OECD Principles on Artificial Intelligence	[53]
	IEEE AI Ethics and Governance Standards	[54]

Despite the increasing development of AI governance frameworks, three key gaps remain insufficiently addressed. First, existing approaches rely on general-purpose or sector-agnostic principles, with limited attention to domain-specific operational requirements in healthcare, where data characteristics, risk profiles, and intervention mechanisms differ significantly across areas such as infectious diseases, behavioural health, and maternal care [15], [27]. Second, current studies do not incorporate context-sensitive and localised

analysis, limiting their ability to account for region-specific factors such as population dynamics, healthcare infrastructure, and large-scale public health pressures, which are particularly pronounced in environments such as Madinah [12], [14], [28]. Third, there is a lack of evidence-driven governance analysis that systematically links large-scale empirical healthcare data with regulatory frameworks, resulting in a disconnection between governance design and real-world system needs [29]. These gaps highlight the need for approaches that integrate domain specificity, contextual awareness, and empirical evidence in the evaluation of AI governance [30].

In this context, this work builds on large-scale, AI-driven literature analysis across multiple domains, including 4,277 publications on healthcare in Madinah (this work), 14,404 publications on AI governance more broadly [31], 4,245 publications on AI governance in neuroinformatics [3], 5,083 publications on interpretability and explainability in healthcare [6], and 2,338 publications on AI in Leukaemia [4], yet no prior work was found that systematically integrates empirical healthcare evidence with governance alignment and gap analysis in a localised setting such as Madinah.

To address these identified gaps, this study adopts an evidence-driven approach to AI governance analysis that integrates large-scale empirical knowledge extraction with structured governance evaluation, enabling a systematic examination of how AI governance frameworks align with healthcare system requirements in Madinah. Our work in this study is structured around two complementary methodological components. First, the PEARL (Parameter Extraction and Refinement Logic) framework is employed to systematically analyse healthcare research and practice in Madinah using a large-scale dataset comprising 4,277 academic publications, producing a structured representation of healthcare priorities in the form of parameters and macro-parameters. Second, the PATHWAY framework is applied as a governance analysis pipeline to evaluate the alignment between these empirically derived healthcare needs and both Saudi Arabian and international AI governance frameworks, enabling the systematic identification of governance gaps, associated risks, and targeted, context-sensitive recommendations.

The analytical logic of the study follows a structured progression in which healthcare evidence informs the identification of potential AI application domains, which are then examined against existing governance frameworks to assess alignment, relevance, and applicability. This process enables the systematic identification of governance gaps and risks, which in turn inform the development of context-sensitive recommendations. Through this pipeline, the study moves beyond abstract governance discussions and establishes a direct connection between empirical healthcare realities and regulatory frameworks.

The results reveal that while existing governance frameworks provide strong foundations in terms of ethical principles, data protection, and risk-based regulation, they lack detailed operational pathways tailored to specific healthcare domains and local contexts. In particular, gaps emerge in areas such as population-specific epidemiological surveillance, behavioural and lifestyle health interventions, maternal and

paediatric healthcare support, environmental health integration, clinical workflow implementation, and generative AI in public health communication. These gaps highlight the need for governance approaches that are not only compliant with high-level principles but also capable of supporting context-aware, scalable, and implementation-ready healthcare AI systems.

In doing so, this study contributes to the emerging field of computational policy analysis by demonstrating how data-driven methodologies can be used to bridge the gap between empirical evidence and governance design. It offers a structured and generalizable approach for evaluating governance frameworks in relation to domain-specific system needs, providing evidence-based insights for policymakers, healthcare practitioners, and researchers.

The main contributions of this study are as follows: First, it introduces an evidence-driven approach to AI governance analysis that integrates large-scale literature mining with structured governance evaluation. Second, it applies the PEARL framework to derive a comprehensive and interpretable representation of healthcare research and practice in Madinah. Third, it employs the PATHWAY framework to systematically assess the alignment between healthcare needs and AI governance frameworks, identifying critical gaps and associated risks. Fourth, it provides targeted recommendations to support the development of context-sensitive, ethically grounded, and operationally viable AI governance strategies for healthcare systems. Finally, it positions Madinah as a real-world empirical environment through which governance frameworks can be tested, evaluated, and refined, offering insights that are applicable to other regions and domains.

The remainder of this study is structured as follows: Section II reviews the literature on AI governance in healthcare, identifies methodological limitations, and outlines the research gap. Section III presents the methodology, introducing the PEARL framework for empirical knowledge discovery and the PATHWAY framework for governance analysis. Section IV provides an empirical characterisation of healthcare needs in Madinah. Section V examines the alignment of AI governance frameworks with public health priorities, covering both Saudi and international perspectives and their comparative analysis. Section VI presents the identified governance gaps, risk implications, and corresponding recommendations. Finally, Section VII concludes the study and outlines directions for future work.

II. LITERATURE BACKGROUND AND RESEARCH GAP

A. AI Governance in Healthcare

The rapid integration of artificial intelligence into healthcare systems has led to the development of a wide range of governance frameworks aimed at ensuring ethical, safe, and trustworthy deployment [1], [6]. These frameworks are typically grounded in high-level principles such as fairness, accountability, transparency, privacy protection, and human oversight, as reflected in major regulatory instruments including data protection laws, ethical AI guidelines, and risk-based regulatory approaches [5], [55].

In addition to general-purpose regulatory instruments, healthcare is supported by sector-specific governance

mechanisms, including guidelines for AI-enabled medical devices, clinical decision-support systems, and digital health technologies [28], [37], [56]. However, these sector-specific provisions primarily focus on compliance, safety, and quality assurance at the system or device level, rather than providing detailed governance approaches tailored to specific healthcare domains or public health functions [57]. As a result, governance remains largely structured around general and sector-level requirements, with limited adaptation to the diverse and dynamic needs of specialised healthcare contexts [38], [58].

This limitation highlights the need for approaches that extend beyond compliance-oriented governance, which primarily focuses on legal and regulatory adherence, toward evaluating whether AI systems are contextually appropriate, operationally effective, and responsive to the dynamic realities of real-world healthcare environments [29], [30].

B. Limitations of Existing Methodologies

A key limitation of current AI governance in healthcare is the lack of empirically grounded, evidence-driven methodologies [59]. Existing frameworks are predominantly principle-based and normative, focusing on defining ethical requirements and regulatory safeguards, but offering limited mechanisms to systematically align governance with observed healthcare system needs, risks, and operational dynamics [60]. As a result, governance approaches remain detached from the empirical realities of healthcare practice, including evolving disease patterns, population-specific characteristics, and system-level constraints.

In addition, current approaches provide limited support for domain-informed governance analysis [29]. While high-level principles are broadly applicable, their translation into contextually relevant and domain-informed governance remains insufficiently supported by systematic analytical approaches [29], [60]. This creates a disconnection between general regulatory guidance and the practical requirements of specialised healthcare applications, where domain-specific risks, data characteristics, and intervention strategies vary significantly.

A further limitation is the lack of context-sensitive and localised governance analysis. Regional healthcare systems such as Madinah operate under unique conditions shaped by demographic diversity and large-scale, recurring population influxes associated with pilgrimage [20]. Annually, the region supports millions of pilgrims for Hajj and Umrah (Official GASTAT statistics indicate that 10.97 million pilgrims performed Umrah in Q3 2025 [21]), creating dynamic and high-pressure public health environments that differ significantly from standard healthcare settings. These conditions introduce complex challenges in areas such as infectious disease surveillance, emergency response, and healthcare resource allocation [22]. At the same time, Madinah is characterised by a rapidly evolving healthcare ecosystem and expanding digital health infrastructure [26]. However, existing governance frameworks rarely incorporate such contextual variability, limiting their ability to support region-specific decision-making and adaptive healthcare responses [61].

C. Research Gap and Contribution

Based on the above limitations, a clear research gap emerges in the absence of systematic approaches that integrate empirical evidence, domain-informed analysis, and contextual sensitivity into AI governance for healthcare. Existing work provides strong normative and regulatory foundations but lacks structured methodologies for linking data-driven insights from healthcare research to governance evaluation.

This study builds on extensive AI-assisted literature analysis across multiple domains. Specifically, PEARL was applied to a large corpus of healthcare research in Madinah (4,277 articles in this study), complemented by prior large-scale analyses of AI governance literature without limiting it to any sectors (14,404 articles, [31]), interpretability and explainability in healthcare (5,083 articles, [6]), AI in Leukaemia (2,338 articles, [4]), and AI governance in neuroinformatics (4,245 articles, [3]). Despite this breadth of analysis, we did not find any prior work that systematically integrates empirical healthcare evidence extraction with structured AI governance evaluation in a unified framework, nor applies such an approach to a context-specific healthcare system such as Madinah.

To address this gap, this study proposes a structured approach that integrates PEARL, for empirical knowledge extraction and synthesis, with PATHWAY, for systematic AI governance assessment. This work provides an empirical and analytical foundation for the systematic identification and evaluation of governance requirements across healthcare domains and contexts, without attempting to fully prescribe domain-specific governance frameworks. This facilitates a data-driven, context-aware analysis of governance alignment, gaps, risks, and recommendations, demonstrated through the case of Madinah's healthcare system.

III. METHODOLOGY

This study adopts an integrated methodology that combines data-driven knowledge discovery with governance analysis to examine the alignment between healthcare needs and AI governance frameworks. The methodology is composed of two complementary components: the PEARL framework for evidence extraction and knowledge structuring, and the PATHWAY framework for governance alignment and gap analysis. Together, these components form a pipeline in which empirically derived healthcare insights inform the evaluation of governance frameworks and the identification of regulatory gaps. Algorithm 1 summarises this integrated PEARL-PATHWAY workflow in procedural form, making explicit the sequential logic through which empirical evidence is transformed into structured governance analysis.

Algorithm 1 presents the PEARL-PATHWAY algorithm for public health AI governance analysis (Madinah).

Algorithm 1: Integrated PEARL-PATHWAY Procedure for Evidence-Driven Governance Analysis in Healthcare

Require: Corpus of healthcare literature for Madinah; Saudi AI governance frameworks; international AI governance frameworks

Ensure: Structured governance insights, identified gaps, risk implications, and recommendations

1. Input Acquisition

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2. Collect healthcare research documents relevant to Madinah
 3. Collect Saudi and international AI governance documents

 4. **PEARL Phase: Empirical Knowledge Discovery**
 5. Apply PRISMA-guided screening and selection
 6. Preprocess textual data (cleaning, tokenization, lemmatization, filtering)
 7. Generate semantic embeddings using BERT-based models
 8. Reduce dimensionality using UMAP
 9. Cluster documents using HDBSCAN
 10. Extract representative themes using BERTopic / c-TF-IDF
 11. Perform iterative quantitative and qualitative validation
 12. Derive validated parameters and macro-parameters representing healthcare system needs

 13. **Evidence-to-Application Mapping**
 14. Map parameters and macro-parameters to healthcare-relevant AI application domains
 15. Identify candidate AI-enabled functions (e.g., surveillance, clinical support, behavioural intervention, communication)

 16. **PATHWAY Phase: Governance Analysis**
 17. Perform policy analysis of Saudi and international governance frameworks
 18. **for** each AI application domain and associated healthcare requirement **do**
 19. Assess regulatory relevance, applicability, and coverage
 20. Evaluate alignment across privacy, safety, ethics, security, and risk classification
 21. Record strengths, partial alignment, and non-alignment
 22. **end for**

 23. **Gap and Risk Identification**
 24. **for** each domain **do**
 25. Identify governance gaps
 26. Analyse associated operational, ethical, legal, and societal risks
 27. **end for**

 28. **Harmonisation and Recommendations**
 29. Formulate targeted, context-sensitive governance recommendations
 30. Relate recommendations to domain-specific healthcare priorities and implementation conditions

 31. **Yield of Governance Insights**
 32. Produce structured outputs on
 - (a) governance alignment,
 - (b) critical gaps and risks,
 - (c) recommended regulatory and operational actions**return** structured evidence-driven AI governance insights for Madinah healthcare
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A. Pearl: Knowledge Discovery and Structuring

The PEARL methodology is employed to systematically extract and structure knowledge from healthcare research and practice in Madinah. PEARL stands for Parameter Extraction and Refinement Logic; for details, see our earlier work [4], [31]. It integrates systematic review principles with advanced machine learning techniques to ensure both methodological rigor and analytical depth. The overall architecture of the

PEARL pipeline is illustrated in Fig. 1, which provides a visual representation of the data collection, processing, clustering, and validation stages. Fig. 2 illustrates the PRISMA flow diagram of the article screening and selection process, while Table II outlines the inclusion and exclusion criteria used during screening.

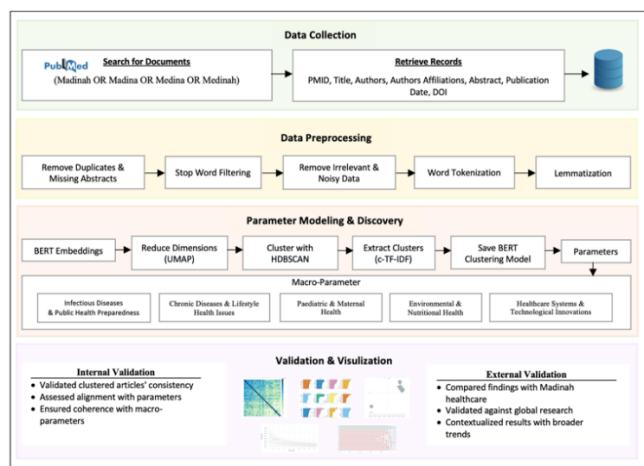


Fig. 1. Public health (Madinah): software methodology and architecture.

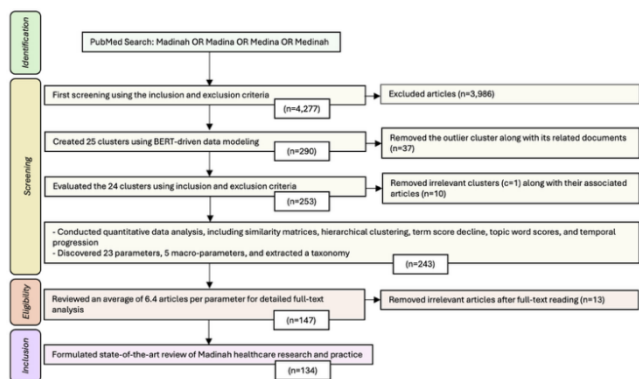


Fig. 2. Evidence foundations for public health (Madinah): PRISMA diagram.

TABLE II. EVIDENCE FOUNDATIONS FOR PUBLIC HEALTH (MADINAH): INCLUSION AND EXCLUSION CRITERIA

Inclusion Criteria	Exclusion Criteria
<ul style="list-style-type: none"> Articles specifically addressing Madinah’s population and healthcare. 	<ul style="list-style-type: none"> Articles unrelated to Madinah and healthcare.
<ul style="list-style-type: none"> Articles pertaining to each parameter, reviewed in full text to assess their relevance, with the objective of validating findings and developing a comprehensive, up-to-date analysis of healthcare research and practice in Madinah. 	<ul style="list-style-type: none"> Duplicate entries identified during the cleaning process and articles without abstract.
<ul style="list-style-type: none"> Clusters generated by BERT that are pertinent to the study’s objectives. 	<ul style="list-style-type: none"> Outlier or irrelevant clusters that do not align with the study’s focus.
<ul style="list-style-type: none"> English-written articles. Published between 2018 and 2023. 	<ul style="list-style-type: none"> Articles not published in English. Articles published before 2018 Articles do not mention the city of Madinah in their titles and abstracts

The dataset was constructed using the PubMed database, based on the query “Madinah OR Madina OR Medina OR Medinah”, and guided by PRISMA principles. A two-stage screening process was applied using clearly defined inclusion and exclusion criteria, resulting in a refined dataset of 243 articles from an initial set of 4,277 records. Pre-processing procedures were conducted to prepare the textual data for computational analysis, including tokenization, lemmatization, and removal of irrelevant information. The processed data were transformed into semantic embeddings using BERT-based models, enabling the capture of contextual relationships between research documents.

Dimensionality reduction was performed using UMAP, followed by clustering through HDBSCAN, resulting in the identification of thematic groupings within the dataset. Clustering using BERTopic further enabled the extraction of representative terms and themes from each cluster, supporting the identification of meaningful knowledge structures. Through iterative refinement and validation, including both quantitative and qualitative assessment, the methodology identified 23 key parameters and five macro-parameters representing the core dimensions of healthcare research and practice in Madinah.

These parameters form the empirical foundation of the study, providing a structured representation of healthcare system needs, challenges, and priorities. This structured knowledge serves as the input to the governance analysis conducted using the PATHWAY framework.

B. Pathway: Governance Analysis Framework

Building upon the empirical knowledge generated through PEARL, the PATHWAY framework is employed to analyse the alignment between healthcare system requirements and AI governance frameworks.

PATHWAY is designed as a general governance analysis pipeline that evaluates how existing regulatory and policy frameworks address domain-specific system needs. It operates through a structured process in which domain knowledge is mapped to governance mechanisms, enabling the identification of alignment, gaps, and associated risks.

The framework structures the governance analysis through a sequence of stages represented by the acronym PATHWAY, encompassing Policy analysis, Alignment assessment, Threat and gap identification, Harmonisation through recommendations, Workflow and oversight considerations, Assurance mechanisms, and Yield of governance insights. This staged structure provides a systematic and replicable approach for evaluating the extent to which governance frameworks address system requirements, while supporting the identification of regulatory gaps and the development of targeted policy responses.

The application of this staged pipeline to the healthcare ecosystem in Madinah is illustrated in Fig. 3, which presents PATHWAY as a structured analytical workflow linking empirical evidence to governance evaluation and policy recommendations. The figure illustrates the PATHWAY AI Governance Framework as a structured analytical pipeline that transforms empirical healthcare evidence into operational governance insights. The framework begins with evidence

foundations derived from large-scale analysis of healthcare research and practice in Madinah, capturing biological, behavioural, environmental, technological, and demographic factors alongside surveillance, prevention, and healthcare delivery dynamics.

These evidence components are translated into key AI application domains, including epidemiological surveillance, behavioural and lifestyle interventions, clinical decision support, maternal and paediatric healthcare systems, environmental health monitoring, and generative AI in public health communication. This intermediate layer establishes a critical link between empirically identified system needs and potential AI-enabled solutions.

The framework then performs governance alignment analysis, evaluating the extent to which these application domains correspond to Saudi Arabian and international AI governance frameworks across dimensions such as regulatory coverage, risk classification, data protection, ethical principles, system security, and healthcare AI safety.

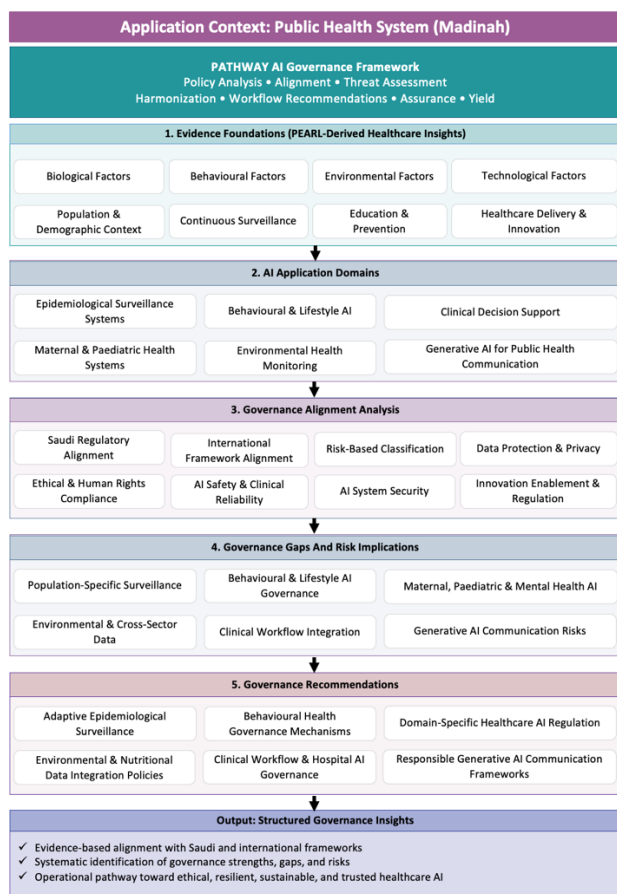


Fig. 3. PATHWAY: Public health (Madinah) AI governance framework.

Building on this alignment assessment, the framework identifies domain-specific governance gaps and associated risk implications, highlighting areas where existing regulatory approaches remain insufficiently operationalized or context-sensitive. These gaps inform a set of targeted governance recommendations that emphasise adaptive, domain-informed, and context-aware policy mechanisms.

The resulting output provides a structured and evidence-driven view of governance alignment, strengths, gaps, and priority actions, offering a coherent pathway for advancing ethical, resilient, and trusted AI deployment within Madinah's healthcare system. This structured pipeline also enables a continuous feedback loop between empirical evidence, governance evaluation, and policy refinement, supporting adaptive and context-sensitive AI governance over time.

In this study, the parameters and macro-parameters derived from PEARL are used as representations of healthcare system requirements in Madinah. These are systematically compared against both Saudi and international AI governance frameworks to assess their relevance, applicability, and coverage.

Through this structured pipeline, the framework enables a systematic assessment of governance effectiveness, supporting the identification of critical areas requiring policy intervention. In line with the Harmonisation stage of PATHWAY, these results inform the development of targeted recommendations aimed at strengthening AI governance for healthcare systems. The resulting insights constitute the Yield of the framework, providing evidence-driven governance intelligence for policy and decision-making.

Although this study focuses on the healthcare ecosystem in Madinah, the PATHWAY framework is designed as a generalizable governance analysis pipeline that can be applied across sectors, domains, and geographical contexts, including different cities and regions.

IV. EMPIRICAL CHARACTERISATION OF HEALTHCARE NEEDS IN MADINAH

This section presents the results derived from the application of the PEARL framework, capturing the key dimensions of healthcare research and practice in Madinah. The analysis identifies 23 parameters grouped into five macro-parameters, which together structure the thematic landscape of healthcare in the region.

These five interconnected macro-parameters collectively reflect the region's healthcare landscape: Infectious Diseases and Public Health Preparedness, Chronic Diseases and Lifestyle Health Issues, Paediatric and Maternal Health, Environmental and Nutritional Health, and Healthcare Systems and Technological Innovations. Each macro-parameter captures a distinct yet complementary dimension of public health, highlighting the interplay between prevention, education, technology, and systemic readiness in improving population well-being.

Fig. 4 presents a taxonomy of this knowledge structure, illustrating the relationships among the macro-parameters and their constituent parameters, and providing a structured view of how healthcare research and practice in Madinah span biological, behavioural, environmental, and technological domains.

Infectious Diseases & Public Health Preparedness highlights resilience within healthcare systems through studies addressing SARS-CoV-2 antibody responses, ICU management during COVID-19, pathogen transmission among Hajj pilgrims, hospital disaster readiness, and radiation safety practices.

Results reveal how pre-existing conditions heighten vulnerability [62], [63], emphasizing the importance of continuous surveillance, scalable infrastructure, and workforce training [64], [65]. It further stresses international collaboration [66] and data-driven public health strategies to ensure sustained readiness for emerging health threats [67].

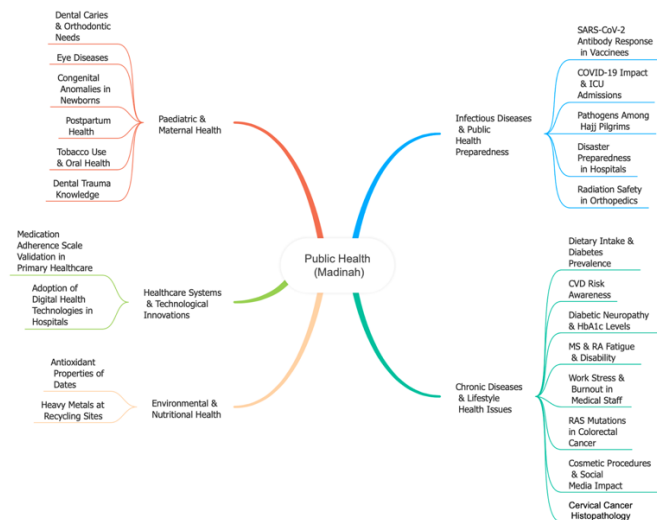


Fig. 4. Public health (Madinah): Knowledge structure and taxonomy.

Chronic Diseases & Lifestyle Health Issues focuses on metabolic and behavioural determinants of health, identifying poor diet, physical inactivity, and limited awareness as major drivers of diabetes, cardiovascular diseases, and related complications [24], [68]. It connects molecular insights, such as RAS gene mutations in colorectal cancer [69], with psychosocial influences including burnout and social media-driven mental health challenges [70], [71]. The studies collectively highlight the need for comprehensive interventions combining education, screening, and lifestyle modification to manage chronic conditions and address gaps in public awareness [24], [72].

Paediatric & Maternal Health reveals a multidimensional nexus of maternal and child well-being shaped by socio-economic, behavioural, and systemic factors. High rates of dental caries [73], congenital anomalies [74], and postpartum depression (PPD) [75] indicate disparities in healthcare access and education. The studies emphasize early screening, parental awareness, and supportive policies for breastfeeding and maternal mental health [76], [77]. Recurring themes include the importance of preventive programs, social support networks, and community-based awareness initiatives in enhancing quality of life and long-term child development [78], [79].

Environmental & Nutritional Health examines the dual role of environmental safety and nutrition in shaping health outcomes. Research on the antioxidant properties of Ajwa dates demonstrates how phenolic compounds reduce oxidative stress and support chronic disease prevention [80], [81]. Conversely, studies on heavy metal contamination at recycling sites expose occupational and environmental hazards associated with cadmium, lead, and other toxic elements [25], [82]. The intersection between these domains reveals how dietary antioxidants may mitigate the effects of environmental toxins

[83]. This macro-parameter underscores the need for integrated policies combining pollution control, agricultural optimization, and nutritional interventions to strengthen population health.

Healthcare Systems & Technological Innovations illustrates the transformation of Madinah’s healthcare landscape through technology and validated clinical tools. Research on medication adherence scale validation [84], [85] demonstrates the necessity of culturally adapted instruments for chronic disease management, while digital health adoption within hospitals such as the Ministry of National Guard Health Affairs (MNGHA) enhances accuracy, efficiency, and patient outcomes [86]. Despite challenges including implementation costs, interoperability issues, and resistance to change [26], the integration of AI, telehealth, and wearable technologies [87], [88] represents a pivotal shift toward data-driven, patient-centric healthcare.

The parameters and macro-parameters identified in this section provide a structured view of healthcare system needs and priorities in Madinah. They present a cohesive picture of health in Madinah, shaped by the intersection of biological, behavioural, technological, and environmental factors. The results highlight key areas of focus, including surveillance, education, preventive interventions, and innovation, reflecting the multidimensional nature of healthcare development in the region. These collectively form the foundation for the subsequent analysis, where their alignment with AI governance frameworks is systematically evaluated using the PATHWAY framework. Table III provides a brief description of the five macro-parameters.

TABLE III. MACRO-PARAMETERS OF HEALTHCARE RESEARCH AND PRACTICE IN MADINAH

Macro-Parameter	Description
Infectious Diseases & Public Health Preparedness	Focuses on disease surveillance, outbreak response, epidemiological monitoring, and preparedness strategies for managing infectious threats at the population level.
Chronic Diseases & Lifestyle Health Issues	Addresses long-term health conditions such as diabetes and cardiovascular diseases, including lifestyle factors, prevention strategies, and population health management.
Paediatric & Maternal Health	Encompasses healthcare services, risk factors, and interventions related to maternal well-being, child development, and early-life health outcomes.
Environmental & Nutritional Health	Examines the impact of environmental conditions, dietary patterns, and nutrition-related factors on public health and disease prevalence.
Healthcare Systems & Technological Innovations	Covers healthcare delivery systems, digital health technologies, data-driven practices, and the integration of innovation into clinical and operational workflows.

V. AI GOVERNANCE ALIGNMENT WITH PUBLIC HEALTH PRIORITIES IN MADINAH

This section applies the PATHWAY framework to evaluate the alignment between the healthcare parameters identified in Section IV and existing AI governance frameworks. The analysis examines the extent to which these frameworks address key dimensions of healthcare research and practice in Madinah, with a focus on their coverage, relevance, and applicability. To provide a comprehensive perspective, the assessment is

conducted across both Saudi (Section IV A) and international governance frameworks (Section IV B), followed by a comparative synthesis that highlights key similarities, differences, and areas of convergence (Section IV C).

A. Saudi AI Governance Frameworks

The healthcare parameters identified in Section IV reflect a multidimensional health landscape in Madinah that intersects with Saudi Arabia's evolving AI and data governance ecosystem. Key national frameworks, including the Personal Data Protection Law [32], the Saudi AI Ethics Principles [12], the Generative Artificial Intelligence Guidelines for Government [33], the Human-Centered AI approach [34], the SFDA guidance on AI and ML-based medical devices [35], and the National Digital Government Strategy [36], collectively establish a foundation for data governance, ethical AI deployment, and digital transformation in healthcare contexts. These frameworks provide a structured basis for understanding how governance mechanisms relate to the healthcare priorities identified in Madinah.

Infectious Diseases & Public Health Preparedness illustrates the need for adaptive, data-driven protection measures. Variability in SARS-CoV-2 antibody responses among different demographic groups and individuals with comorbidities underscores the value of continuous monitoring and targeted vaccination strategies [62]. The Personal Data Protection Law [32] provides safeguards for such health surveillance by regulating lawful and minimal data processing, particularly when handling sensitive health data. The significant strain on ICU capacity due to delayed medical care, pre-existing illnesses, and high viral load at diagnosis [62], [63] reinforces the importance of reliable clinical analytics governed by the Saudi AI Ethics Principles, which emphasize fairness, transparency and human oversight. The unique risks associated with Hajj gatherings [19], [20] demonstrate the benefit of AI-assisted early warning systems in governmental settings, but these must comply with the Generative Artificial Intelligence Guidelines for Government that require accuracy, controlled use of restricted data and clarity when automated content informs public messaging. Hospital disaster readiness supported by accreditation and professional training [65] aligns with the National Digital Government Strategy through strengthened digital response infrastructure. Radiation exposure risk in orthopaedics [89] also points toward safe adoption of AI-assisted imaging tools, falling under SFDA guidance on AI and ML technologies-based medical devices to ensure validated clinical performance.

Chronic Diseases & Lifestyle Health Issues highlight the importance of preventive health technologies and patient empowerment. High consumption of sugary beverages and fast foods correlates with diabetes risk in the Madinah population including students [24], [68], and limited awareness of cardiovascular dangers affects early detection and lifestyle choices [23]. Human-Centered AI principles support digital tools that facilitate health education and behavioural change while maintaining inclusivity. Diabetic neuropathy results [90] indicate that remote monitoring and personalised care tools could assist disease management under ethical controls. Work stress and burnout among healthcare professionals [70] suggest that AI may help optimise workload and reduce fatigue when

deployed responsibly under the Saudi AI Ethics Principles and accountability provisions. In cancer care, molecular determinants of colorectal cancer [69] signal the future integration of AI-enabled diagnostic systems whose safety would be regulated through SFDA guidance on AI and ML technologies-based medical devices. The influence of social media on cosmetic interventions [71] and persistent gaps in cervical cancer awareness [91] underline opportunities for reliable and culturally aligned generative AI public health communication under strict regulatory controls in the Generative Artificial Intelligence Guidelines for Government.

Paediatric & Maternal Health requires AI solutions that support equity and family wellbeing. High rates of childhood dental caries and unmet orthodontic needs [73], [78] stem from socio-economic and behavioural factors that can be targeted through digital outreach informed by the Saudi AI Ethics Principles [12] commitment to fairness. Reliance on natural remedies for oral conditions [92] highlights trust gaps that digital tools could help address if they align with cultural sensitivities emphasized in Human-Centered AI [34]. Limited awareness of paediatric eye diseases [93] suggests that parental engagement platforms could assist early detection when compliant with Personal Data Protection Law safeguards. Maternal health concerns, such as postpartum depression and breastfeeding challenges [75], show the need for tele-mental health and decision-support systems that enhance, rather than replace, professional support networks. Evidence associating caesarean delivery with childhood ASD risk [94] calls for decision aids that improve understanding of medical choices under strong human oversight and risk transparency. Widespread tobacco use and inadequate preparedness for dental trauma [95] similarly support the use of structured educational AI tools guided by the Generative Artificial Intelligence Guidelines for Government.

Environmental & Nutritional Health demonstrates how nutrition and environmental safety can both benefit from AI-supported monitoring. The protective effects of antioxidants in dates, particularly Ajwa varieties [96], support nutritional analytics that remain compliant with the Personal Data Protection Law [32] when integrated with health records. Meanwhile, heavy metal exposure at recycling sites poses significant respiratory risks [25], [82], and the Saudi AI Ethics Principles [12] and National Digital Government Strategy [36] could enable predictive environmental modelling that informs health protection, provided transparency and accountability are upheld. Nutritional strategies that reduce oxidative stress through metal chelation [83] further highlight the value of integrated analytics across food and environmental data.

Healthcare Systems & Technological Innovations illustrate direct intersections with national digital policy and biomedical AI regulation. Medication adherence research [97] suggests that predictive adherence analytics can support chronic disease control if aligned with Personal Data Protection Law principles of consent and security. The expanding digital health environment in Madinah's hospitals, including electronic records and telehealth [87], reinforces the National Digital Government Strategy objectives related to secure interoperability and efficient service delivery. As AI applications evolve within hospital workflows, they must

operate under the Saudi AI Ethics Principles and SFDA guidance on AI and ML technologies-based medical devices [35], where clinical impact is concerned.

Across these macro-parameters, Saudi AI governance frameworks demonstrate varying levels of alignment with the healthcare priorities identified in Madinah. Stronger alignment is observed in areas related to digital infrastructure, data governance, and healthcare system transformation, while more domain-specific applications are less explicitly represented within current governance provisions. Therefore, the analysis indicates that national frameworks provide a coherent foundation for supporting AI-enabled healthcare development, with alignment varying across different dimensions of the healthcare system.

B. International AI Governance Frameworks

The healthcare parameters identified in Section IV can be examined in relation to international AI governance frameworks, which provide structured approaches to regulating AI applications in healthcare and other high-impact domains. Prominent frameworks emphasise principles such as risk-based classification, transparency, accountability, human oversight, and data protection, offering a broader context for assessing how governance mechanisms align with the healthcare priorities observed in Madinah. National strategic frameworks such as the UK National AI Strategy [10], Japan's AI Strategy [46], Canada's AI Strategy for the Federal Public Service [48], and China's New Generation AIDP [11] articulate how these principles are operationalized at the policy level, particularly in guiding responsible AI adoption, public sector integration, and data governance across domains, including healthcare.

For instance, the challenges of managing infectious diseases, including COVID-19, and the unique public health risks during the Hajj pilgrimage resonate with the risk-based frameworks established by the EU AI Act [7]. Its classification of AI systems by risk underscores the importance of targeted oversight for applications such as pandemic surveillance, predictive analytics for ICU admissions, and diagnostic tools that can mitigate risks during large gatherings such as Hajj [62], [64]. Similarly, the US Blueprint for an AI Bill of Rights [8] and the Executive Order on AI [9] emphasize transparency, fairness, and accountability, principles that are directly relevant to building trust in AI-driven surveillance systems and diagnostic platforms in Madinah [67], [98].

The preparedness of hospitals in Madinah, as shown in studies on disaster readiness and ICU capacity, also intersects with the EU's Medical Device Regulation (MDR) [37] and In Vitro Diagnostic Regulation (IVDR) [38], which mandate ongoing monitoring and risk assessment for AI-enabled medical devices. These frameworks provide valuable guidance for ensuring that technologies adopted in Madinah's hospitals, including AI-driven diagnostic imaging or ICU monitoring, comply with safety and transparency requirements [99], [100]. Likewise, the US FDA's Software as a Medical Device (SaMD) framework [44] establishes robust standards for clinical evaluation, post-market surveillance, and patient safety, aligning with Madinah's emphasis on scalable healthcare infrastructure and continuous training of professionals [89], [101].

Chronic diseases and lifestyle health issues, such as diabetes, cardiovascular conditions, and cancer, represent a growing burden in Madinah. Here, AI governance frameworks addressing privacy and data protection play a pivotal role. The GDPR [39] in Europe stresses informed consent, transparency, and secure data management. These provisions are critical for managing sensitive health records, dietary surveys, and genetic information that underpin chronic disease research in Madinah [68], [102], [103]. Additionally, Japan's Act on the Protection of Personal Information (APPI) [47] and Canada's PIPEDA [49] reinforce the global consensus that privacy-preserving practices are indispensable when handling healthcare data for both research and clinical applications. This is particularly relevant for initiatives in Madinah aimed at improving public awareness of cardiovascular risks or managing diabetes through digital health tools [23].

Maternal and paediatric health results, including postpartum depression, congenital anomalies, and orthodontic needs, further highlight the need for ethical AI integration. The UNESCO Recommendation on the Ethics of AI [52] and the WHO guidance on AI in healthcare [28] call for equity, inclusiveness, and respect for human rights in deploying AI in clinical and community contexts. These frameworks support the design of AI-based early detection tools for congenital anomalies or mental health risks, ensuring that vulnerable groups, including women and children, benefit from technology without being exposed to additional ethical or privacy risks [73], [74], [75]. Similarly, UK GDPR [42] and the oversight of the Information Commissioner's Office (ICO) offer lessons in balancing innovation with protection of sensitive maternal and paediatric health data [93].

Environmental and nutritional health concerns in Madinah, such as antioxidant research on dates and heavy metal contamination at recycling sites, highlight another dimension of global AI governance. Regulations such as the EU NIS2 Directive [40] and Singapore's Regulatory Guidelines for Software Medical Devices [51] emphasize the role of cybersecurity and lifecycle monitoring in environmental and health-related AI systems. These frameworks can inform the design of AI-driven environmental monitoring tools that track pollution or food safety risks in Madinah, ensuring data integrity and reliability while protecting public health [96], [104]. Additionally, the EU's green deal [41] provides guidance on environmental issues by promoting sustainability, pollution reduction, and the integration of digital and data-driven approaches to support environmental monitoring and public health protection.

Finally, the adoption of digital health technologies and the validation of medication adherence tools in Madinah reflect the opportunities and challenges of technological innovation. The NIST AI RMF [45], the UK's use of regulatory sandbox [43], and China's Generative AI Regulation [50] collectively illustrate global recognition of the need for flexible but accountable oversight of emerging technologies. These initiatives provide a blueprint for Madinah's healthcare system to adopt AI responsibly, balancing innovation in digital health with safeguards for data security and patient trust [97], [105], [106].

International frameworks, such as those of the OECD [53] and IEEE [54], reinforce this balance by promoting transparency, robustness, and accountability across healthcare innovations [84], [107], [108].

Across these macro-parameters, international AI governance frameworks demonstrate a generally higher level of explicit coverage, particularly in areas involving high-risk applications, clinical decision support, and system-level accountability. This results in stronger alignment with several healthcare parameters identified in Madinah, especially those related to infectious disease management and healthcare system oversight. However, certain domains, including environmental and nutritional health, are less prominently represented within current governance provisions. Overall, international frameworks provide a comprehensive conceptual and regulatory basis, with alignment varying across different dimensions of healthcare.

C. Comparative Alignment

The comparative analysis of Saudi and international AI governance frameworks reveals both convergence and variation in their alignment with healthcare priorities identified in Madinah. Saudi frameworks demonstrate a strong emphasis on digital transformation, data governance, and the integration of AI within national development strategies. This results in relatively strong alignment with healthcare systems and

technological innovation, as well as broader public health infrastructure.

In contrast, international frameworks provide more structured and mature approaches to AI governance, particularly through risk-based classifications, accountability mechanisms, and explicit consideration of high-risk applications in healthcare. These frameworks show stronger alignment with areas such as infectious disease monitoring, clinical decision support, and system-level oversight.

Differences also emerge in the extent to which specific healthcare domains are explicitly addressed. While some areas receive considerable attention across both governance contexts, others, including environmental and nutritional health, as well as context-specific aspects of paediatric and maternal healthcare, are less prominently reflected. These variations indicate differing priorities, levels of maturity, and approaches to operationalizing AI governance across contexts.

The analysis presented in this section suggests that Saudi frameworks are evolving and implementation-oriented, whereas international frameworks provide broader conceptual and regulatory structures. Together, they offer complementary perspectives that inform a more comprehensive understanding of AI governance in healthcare. Table IV summarises this comparative synthesis.

TABLE IV. COMPARATIVE ALIGNMENT OF AI GOVERNANCE FRAMEWORKS WITH MADINAH HEALTHCARE MACRO-PARAMETERS

Macro-Parameter	Saudi Frameworks	International Frameworks
Infectious Diseases & Public Health Preparedness	Moderately aligned through data governance and digital health initiatives; limited explicit AI-specific articulation	Strongly aligned through risk-based governance, monitoring, and system validation requirements
Chronic Diseases & Lifestyle Health Issues	Moderately reflected within preventive health and digital transformation strategies	Moderately aligned through clinical AI governance and decision-support frameworks
Paediatric & Maternal Health	Broadly addressed within general healthcare policies; limited explicit AI governance focus	Partially reflected under general healthcare AI risk classifications
Environmental & Nutritional Health	Indirectly reflected within sustainability and public health initiatives	Limited explicit representation within current AI governance frameworks
Healthcare Systems & Technological Innovations	Strongly aligned through national AI strategies and digital health transformation	Strongly aligned through comprehensive regulatory, ethical, and operational frameworks

VI. AI GOVERNANCE GAPS, RISK IMPLICATIONS, AND RECOMMENDATIONS

Despite strong alignment between Madinah's healthcare priorities and both Saudi Arabian and international AI governance frameworks, several important gaps remain where regulatory provisions do not fully accommodate the practical and contextual realities revealed by empirical results. Within the PATHWAY framework, this stage corresponds to the systematic identification of governance gaps and associated risks following alignment assessment, forming the basis for subsequent harmonisation through targeted recommendations. Foundational instruments such as the Personal Data Protection Law [32] and the Saudi AI Ethics Principles [12] provide robust safeguards for lawful data processing, oversight, and ethical AI deployment. Similarly, international risk-based frameworks, including the EU AI Act [7] and the US Blueprint for an AI Bill of Rights [8] emphasize accountability, transparency, and protection from harm. However, while these frameworks establish strong normative foundations, they provide limited operational guidance for population-specific, dynamic epidemiological surveillance.

Empirical evidence from Madinah demonstrates highly variable SARS-CoV-2 antibody responses and ICU demands influenced by comorbidities [62], [63], alongside intensified public health pressures during large-scale gatherings such as the Hajj [19], [20]. Although existing policies ensure responsible data governance, they do not sufficiently define structured pathways for continuous, event-driven epidemiological analytics tailored to demographic variability and localized health risks. This gap creates the risk of reduced responsiveness to rapidly evolving public health conditions. Addressing this limitation requires strengthening regulatory provisions to explicitly support context-sensitive, real-time surveillance systems that operate within clear accountability and privacy safeguards.

Similar regulatory limitations appear in the governance of behavioural and lifestyle-focused AI health tools. Human-Centered AI principles and privacy protections embedded within frameworks such as GDPR [39], PIPEDA [49], and APPI [47] reinforce secure handling of health data. Nevertheless, chronic disease drivers in Madinah, including dietary habits, cardiovascular risk unawareness, and lifestyle-related

conditions [102], [109], [110], reveal insufficient regulatory direction for AI systems designed to influence behavioural change, promote dietary awareness, or engage youth populations in preventive health practices. Ethical principles exist, yet they lack detailed guardrails for culturally sensitive behavioural intervention technologies. Without clearer governance mechanisms, such systems risk ethical ambiguity or misalignment with local values. Therefore, structured oversight frameworks for behavioural and lifestyle-oriented AI tools should be established to ensure culturally appropriate, prevention-focused digital health interventions that maintain strong privacy protections.

Further governance gaps emerge in maternal, paediatric, and mental health domains. International instruments such as UNESCO's Recommendation on the Ethics of AI [52] and WHO guidance on health AI [28] emphasize fairness, inclusivity, and protection of vulnerable populations, and Saudi frameworks similarly recognize societal and cultural values. However, Madinah results identify unmet orthodontic needs [111], limited awareness of paediatric eye diseases [93], postpartum mental health challenges [75], and broader maternal decision-support gaps. Existing regulatory structures lack specialised operational pathways for AI-assisted screening, tele-support systems, and child- or mother-focused digital health platforms. This creates ethical and trust-related risks for vulnerable groups. Developing specialised governance provisions tailored to maternal, paediatric, and mental health AI systems would strengthen ethical implementation, reinforce clinical oversight, and enhance trust by aligning digital interventions with family-centred and culturally grounded values.

Environmental and nutritional health governance also remains insufficiently integrated within current AI regulatory frameworks. The Saudi AI Ethics Principles [12] and the National Digital Government Strategy [36] promote responsible digital transformation, and instruments such as the EU NIS2 Directive [40] and Singapore guidelines [51] reinforce cybersecurity and lifecycle oversight for digital infrastructures that process cross-sector environmental and health data. However, empirical results from Madinah highlight health threats associated with heavy metal exposure at recycling sites [25], [82] and complex relationships between local dietary practices and antioxidant intake [112], [113]. Current governance structures do not clearly articulate how environmental monitoring data should be securely integrated with health analytics systems. This fragmentation limits transparent risk modelling and cross-sector accountability. Integrating environmental and nutritional data streams into AI governance architectures would enable secure cross-sector data sharing, strengthen predictive public health analytics, and enhance transparent risk management.

Oversight challenges also extend to AI-enabled medical devices and clinical workflow integration. Regulatory foundations are strong, with SFDA guidance [35], the EU MDR [37], IVDR [38], US SaMD requirements [44], and the Executive Order on AI [9] establishing safety, quality, and post-market monitoring standards. Nonetheless, Madinah results underscore the importance of scalable AI deployment in

hospitals, workforce capacity-building, and digital systems that support treatment adherence and operational efficiency [26], [97], [101].

Current governance models prioritize technical compliance and safety validation but remain under-specified in relation to hospital-level adoption processes, workforce training, and real-world integration metrics. This creates implementation risks even where technical standards are satisfied. Expanding governance frameworks to include structured oversight for clinical adoption readiness, professional training, and workflow integration would strengthen real-world safety and performance.

Finally, governance of generative AI in public health communication remains underdeveloped. Although instruments such as the Generative Artificial Intelligence Guidelines for Government [33] promote transparency and responsible deployment, and broader international controls emphasize accountability, empirical results reveal persistent misinformation challenges in cosmetic decision-making [71], limited cervical cancer awareness [91], and inadequate responses to paediatric injuries [114]. Existing policies do not sufficiently ensure that AI-generated health content is culturally appropriate, clearly attributable, and responsive to local health literacy variations. Without strengthened safeguards, generative systems risk amplifying misinformation or eroding public trust. Strengthening governance for culturally aligned generative AI in healthcare communication would ensure transparent attribution, content validation mechanisms, and literacy-sensitive design standards that support improved community health outcomes.

Therefore, across these domains, a broader structural pattern emerges. Many governance frameworks articulate high-level principles of fairness, accountability, privacy, and transparency, yet lack detailed operational pathways tailored to specific demographic, epidemiological, environmental, and institutional contexts. This operationalization gap, combined with limited cross-sector integration and insufficient implementation-readiness mechanisms, constrains the full realization of AI-enabled healthcare benefits in Madinah. From a PATHWAY perspective, these gaps highlight the need for structured harmonisation through targeted recommendations and governance refinement. Addressing these interconnected gaps through targeted regulatory refinement will enable governance systems not only to uphold foundational ethical standards but also to support culturally aligned, context-sensitive, and operationally scalable AI deployment. In doing so, Madinah's healthcare ecosystem can advance equitable, resilient, and technology-enabled outcomes aligned with both national priorities and international best practices.

Fig. 5 synthesises the identified AI governance gaps in Madinah's healthcare ecosystem, highlighting their associated risks and the corresponding recommendations required to support context-sensitive, scalable, and ethically aligned AI deployment. Moreover, Table V provides a structured overview of domain-specific AI governance gaps in Madinah's public health system, linking each gap to its corresponding risk implications and targeted governance recommendations.

Public Health (Madinah): AI Governance Gaps, Risks Implications, & Recommendations

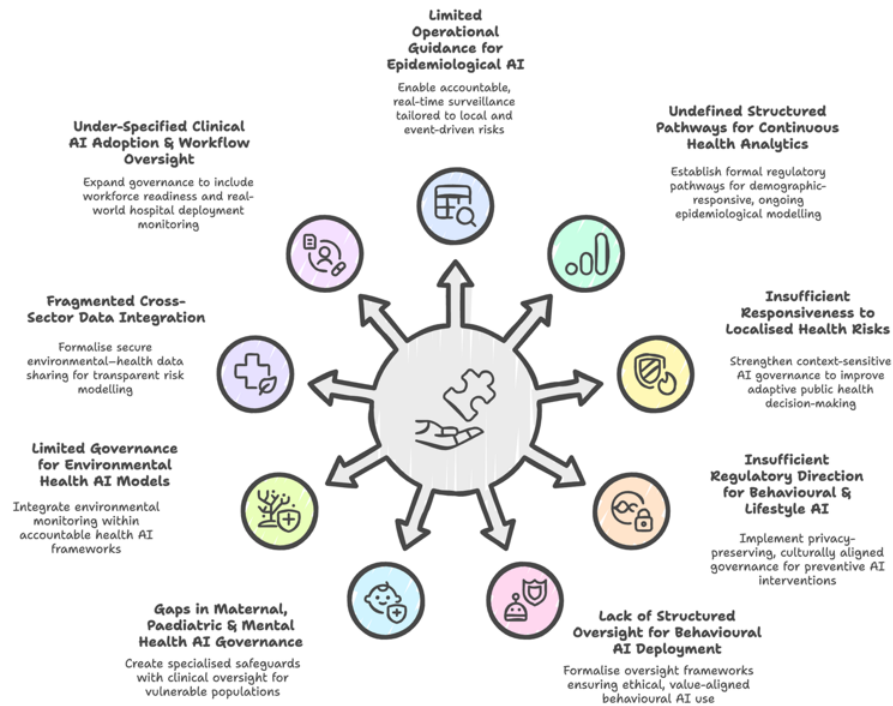


Fig. 5. Public health (Madinah): AI governance gaps, risk implications, and recommendations.

TABLE V. DOMAIN-LEVEL AI GOVERNANCE GAPS, RISK IMPLICATIONS, AND RECOMMENDED ACTIONS IN PUBLIC HEALTH (MADINAH)

Domain	Key Governance Gap	Risk Implication	Recommendation
Infectious Diseases & Public Health Preparedness	Lack of explicit governance for real-time epidemiological AI systems	Reduced responsiveness to dynamic outbreaks	Introduce regulatory pathways for real-time surveillance and model validation
Chronic Diseases & Lifestyle Health Issues	Limited guidance for behavioural and preventive AI systems	Ethical ambiguity and misalignment with cultural values	Develop governance for culturally sensitive behavioural AI tools
Paediatric & Maternal Health	Absence of specialised provisions for vulnerable populations	Safety and trust risks in sensitive healthcare domains	Establish tailored governance for child and maternal AI applications
Environmental & Nutritional Health	Weak integration of environmental data in AI governance	Fragmented risk modelling and limited cross-sector insight	Enable secure integration of environmental and health data systems
Healthcare Systems & Technological Innovation	Insufficient focus on implementation and workforce readiness	Deployment and adoption risks in real-world settings	Expand governance to include training, workflow integration, and monitoring
Generative AI in Public Health	Limited safeguards for health communication systems	Risk of misinformation and reduced public trust	Introduce governance for culturally aligned and validated AI-generated content
Mass Gathering and Event-driven Public Health Systems	Lack of governance for AI systems operating in large-scale, dynamic population environments (e.g., Hajj)	Reduced responsiveness and coordination in high-density, rapidly evolving public health scenarios	Develop governance frameworks for event-driven, real-time population health analytics and coordination systems
Demographic Variability and Personalised Public Health	Limited governance for AI models handling heterogeneous population characteristics and responses	Reduced fairness, accuracy, and reliability in population-level predictions and interventions	Introduce governance provisions for adaptive, demographic-aware AI systems and model validation across diverse groups
Clinical Workflow Integration and Adoption Readiness	Governance frameworks do not sufficiently address hospital-level integration, workflow embedding, and adoption processes	Implementation failures despite technical compliance; reduced efficiency and usability in clinical settings	Extend governance to include operational readiness, workflow integration standards, and clinical deployment guidelines
Real-world Monitoring and Lifecycle Oversight	Insufficient operationalization of continuous monitoring, validation, and feedback mechanisms for deployed AI systems	Undetected model drift, reduced reliability, and long-term performance degradation	Establish lifecycle governance models with continuous evaluation, auditing, and post-deployment monitoring
AI-enabled Public Health Communication Systems	Limited governance for AI-mediated health communication beyond general principles (including but not limited to generative AI)	Risk of misinformation, low health literacy alignment, and erosion of public trust	Develop governance mechanisms for transparent, culturally aligned, and validated AI-driven health communication systems

VII. CONCLUSION

This study has examined the alignment between healthcare system needs and AI governance frameworks through an evidence-driven and context-sensitive approach. By integrating large-scale empirical analysis of healthcare research and practice in Madinah with structured governance evaluation, the study demonstrates how governance frameworks can be systematically assessed against real-world system requirements. The combined application of the PEARL and PATHWAY frameworks enables a coherent analytical pipeline that connects empirical evidence, potential AI applications, governance alignment, and the identification of gaps, risks, and recommendations.

The results indicate that while existing Saudi Arabian and international AI governance frameworks provide strong foundations in terms of ethical principles, data protection, and risk-based regulatory models, they remain insufficiently operationalized for domain-specific and context-sensitive healthcare applications. In particular, gaps emerge in areas requiring continuous and adaptive responses, including epidemiological surveillance, behavioural and lifestyle health interventions, maternal and paediatric care, environmental health integration, clinical workflow implementation, and the governance of AI-generated public health information. These limitations reflect a broader structural issue in which high-level governance, although necessary, does not fully translate into operational and context-aware mechanisms within complex healthcare environments.

This work contributes to addressing this gap by demonstrating the value of linking empirical healthcare evidence with governance analysis. Rather than relying solely on abstract regulatory principles or isolated case studies, the approach adopted in this study enables a systematic and data-informed understanding of how governance frameworks interact with real-world healthcare needs. In doing so, it highlights the importance of moving towards governance models that are not only principle-based but also supported by structured evidence, capable of capturing evolving system dynamics, and responsive to local conditions.

Furthermore, our study underscores the importance of governance approaches that are supported by continuous and iterative analysis of healthcare data, research developments, and societal needs, forming a structured feedback loop in which evidence generation, governance evaluation, and policy refinement are perpetually linked (see our earlier works, e.g., [115], [116], [117]). Such an approach enables governance systems to evolve in response to emerging risks, new evidence, and changing public health conditions, while maintaining transparency, traceability, and accountability. By embedding this continuous evaluation and refinement cycle into governance processes, policymakers can develop more responsive and adaptive strategies, improve the reliability of health communication, and strengthen public trust by ensuring that AI-enabled systems remain aligned with both scientific evidence and community realities. This perspective is consistent with emerging approaches that emphasise systematic, data-driven analysis as a foundation for ongoing policy monitoring and refinement.

The study also positions Madinah as a meaningful empirical environment for governance evaluation, demonstrating how localised analysis can reveal insights that are not visible in global or purely conceptual studies. The methodological approach and results are therefore not limited to this context but offer a generalizable framework for analysing AI governance in other regions and domains characterised by complex, dynamic, and data-intensive systems.

Therefore, advancing AI governance in healthcare requires moving beyond high-level principles towards evidence-driven, domain-informed, and context-aware operationalization. By bridging empirical analysis with governance evaluation, this study contributes to the development of more adaptive, scalable, trustworthy, and sustainable governance strategies, supporting the effective and responsible integration of AI into healthcare systems.

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