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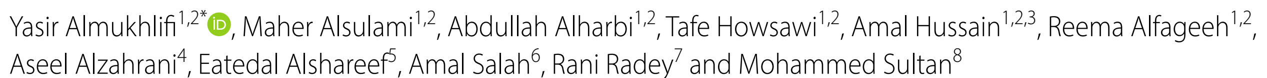

REVIEW Open Access

Strengthening hospital resilience to earthquakes: a public health review of seismic risk reduction programs in the Middle East

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Abstract

Introduction Maintaining hospital functionality during and after earthquakes is essential for effective disaster response in seismically active regions. In the Middle East, hospital resilience is challenged by limited infrastructure investment, variable enforcement of safety regulations, and inconsistent preparedness planning.

Methods A systematic literature review was conducted across nine databases (2009–2024), including EBSCO, Cochrane, PsycINFO, Scopus, Web of Science, PubMed, Medline, EconLit, and Google Scholar. Studies were included if they assessed hospitals in the Middle East with comprehensive or partial seismic risk reduction programs. Three independent reviewers performed data extraction and quality appraisal using validated tools appropriate to study design.

Results Five studies met the inclusion criteria. Hospitals with comprehensive seismic risk reduction programs, including structural retrofitting, disaster drills, surge capacity plans, and emergency communication protocols, demonstrated higher levels of functional continuity following earthquakes. In contrast, facilities lacking such measures reported structural damage, service disruptions, and patient evacuations. Mobile hospitals were identified as a promising adaptive strategy for mitigating overload in high-risk, resource-limited settings.

Conclusion Comprehensive seismic preparedness programs enhance hospital functionality in earthquake-prone regions. These findings underscore the importance of integrated risk reduction strategies, cross-sector coordination, and sustained investment. Further research is needed to evaluate the comparative impact of preparedness levels using standardized functionality indicators, and to explore scalable innovations such as mobile and modular healthcare units to strengthen regional disaster resilience.

Keywords Hospitals, Disaster planning, Earthquakes, Emergency preparedness, Risk management, Middle east

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Introduction

Hospitals and healthcare systems play a pivotal role in the aftermath of large-scale emergencies and crises [1]–[2]. To ensure effective disaster response and continuity of care, it is essential that healthcare infrastructure remains operational throughout such events [3]. This is primarily achieved through the implementation of seismic risk reduction strategies, which encompass various interventions designed to mitigate the impact of earthquakes on infrastructure, essential services, and human lives. However, earthquakes can cause devastating damage to healthcare facilities, compromising their ability to deliver care when it is most needed. Seismic risk reduction protects hospital structures and operations, enabling them to remain functional during and after earthquakes.

Seismic risk reduction strategies in hospitals focus on both structural and non-structural components. Structural retrofitting involves reinforcing hospital buildings to withstand seismic forces, such as installing shear walls, base isolators, and reinforced foundations [4]. Base isolators are flexible bearings placed between a building and its foundation that absorb seismic energy, allowing the structure to move independently of ground motion. These modifications are essential for reducing the likelihood of building collapse and ensuring the safety of patients, healthcare workers, and medical equipment.

Alongside structural elements, non-structural measures are equally important for maintaining hospital functionality. In this review, hospital functionality refers to the capacity of a healthcare facility to maintain essential clinical and support services during and after a seismic event, including uninterrupted delivery of critical care, emergency services, and logistical support, without requiring evacuation or significant service downtime. These include securing medical equipment, training hospital staff in disaster response protocols, and developing hospital disaster plans that align with local emergency frameworks [5]. To complement these efforts, hospitals must also coordinate with external agencies, managing patient surges (surge capacity refers to the ability of a healthcare facility to rapidly expand its services beyond normal capacity to accommodate a sudden and sustained increase in patient volume), ensuring the availability of critical supplies, and maintaining operations during disasters. This multi-layered approach improves a hospital's capacity to respond effectively, maintain logistical continuity, and provide uninterrupted care in the face of severe disruptions [6].

These elements are consistent with established international frameworks, such as the World Health Organization's Safe Hospitals Framework, which emphasizes structural safety, functional continuity, and effective emergency management, and FEMA 396 guidelines, which outline technical criteria for the seismic performance of healthcare facilities. The operational definition of "comprehensive seismic risk reduction programs" used in this review aligns with these standards by integrating structural retrofitting, functional preparedness, and governance mechanisms into a unified approach to hospital resilience.

While these measures are critical, their implementation is far from straightforward, particularly in resource-constrained regions such as the Middle East. In addition to financial limitations, hospitals face shortages of technical expertise and weak disaster-preparedness regulations [3]. Disparities between urban and rural facilities further exacerbate the vulnerability of healthcare infrastructure in less developed areas [7]. Budgetary constraints may delay seismic retrofitting, leaving hospitals reliant on outdated buildings not designed to withstand earthquakes. Many institutions also lack the resources for staff training and emergency drills, further compromising their capacity for effective disaster response [5]. Overcoming these challenges requires coordinated investment and leadership from governments, healthcare providers, and international organizations.

Several studies in Middle Eastern countries have evaluated various aspects of hospital disaster preparedness, but they often suffer from limitations such as narrow scope, limited generalizability, or an exclusive focus on individual preparedness domains. For instance, a study in Damghan, Iran, found moderate levels of functional preparedness (45.8%) and highlighted structural vulnerabilities, recommending improved disaster education and exercises for healthcare staff [8]. However, the study's Limited geographic scope prevents generalization to a broader population. A survey conducted across 15 hospitals affiliated with Shahid Beheshti University in Iran reported 86.7% demonstrating good overall preparedness, but with a relatively low construction mitigation score (56.6%), indicating structural weaknesses [9]. This study stressed the importance of integrating disaster plans with drills and hospital curricula. Another study in Turkey proposed a model using mobile hospitals to address surge demand during earthquakes, demonstrating how such systems can optimize resource reallocation and enhance care delivery in seismically vulnerable settings [10].

While these and other studies from Iran and Saudi Arabia provide valuable insights, they tend to focus on isolated components of preparedness, such as structural safety, administrative planning, or staff training, without assessing how these elements collectively influence hospital functionality. A comprehensive, region-wide comparison remains lacking, particularly one that integrates both structural and non-structural dimensions. Moreover, most existing studies are retrospective in nature,

limiting their ability to inform proactive, future-facing resilience strategies.

To address these gaps, this study evaluates whether hospitals in the Middle East that have implemented comprehensive seismic risk reduction programs demonstrate higher functional continuity after major earthquakes compared to hospitals with partial or no such measures.

For the purposes of this review, a *comprehensive seismic risk reduction program* is defined as an integrated set of measures that, at minimum, include: (1) structural retrofitting interventions to strengthen building integrity (e.g., base isolation systems, reinforcement of load-bearing structures); (2) functional preparedness components such as surge capacity planning, regular disaster drills, and continuity of operations protocols; and (3) governance and coordination mechanisms ensuring alignment of hospital disaster plans with national or regional emergency management systems. Programs lacking one or more of these core components were categorized as partial or non-comprehensive.

Methodology

Systematic literature review design

The primary objective of this systematic review is to evaluate whether hospitals in earthquake-prone regions of the Middle East with seismic risk reduction programs maintain higher functionality after seismic events compared to those with partial or no such programs. The review focused on hospitals located in areas with documented seismic activity, including the Zagros Mountains in Iran, Eastern Turkey near the North Anatolian Fault, Northern Iraq, Lebanon, Northern Syria, Jordan along the Dead Sea Fault system, and seismically vulnerable regions in Armenia and Kuwait.

Data collection

Databases

A comprehensive literature search was conducted across nine databases: EBSCO, Cochrane, PsycINFO, Scopus, Web of Science, PubMed, Medline, EconLit, and Google Scholar. These databases were selected to ensure broad coverage of multidisciplinary evidence relevant to hospital functionality in post-earthquake settings, with an emphasis on their applicability to the research topic. Google Scholar was included to capture grey literature and relevant reports not indexed in traditional academic databases. The search strategy was developed through a systematic approach and employed a combination of keywords and Medical Subject Headings (MeSH) terms related to seismic risk reduction programs. A complete example of the search string used for MEDLINE, including Boolean operators and applied filters, is provided in Appendix 1 to enhance transparency and reproducibility. The search was restricted to studies published between 2009 and 2024, ensuring the relevance and contemporary nature of research findings related to hospital functionality in post-earthquake regions of the Middle East. By focusing on this 15-year timeframe, the review will capture the latest evidence reflecting current practices, challenges, and advancements in hospital functionality following earthquakes, which are crucial for understanding how hospitals adapt and function in such events.

Inclusion and exclusion criteria

To be eligible for inclusion, studies had to report on hospitals implementing comprehensive or partial seismic risk reduction programs. In this review, "comprehensive" seismic risk reduction programs were defined as those meeting all three minimum criteria: (1) structural retrofitting measures to improve seismic safety (e.g., base isolation, reinforcement of load-bearing structures); (2) functional preparedness activities, including disaster drills, surge capacity planning, and continuity of operations protocols; and (3) governance and coordination mechanisms that integrate hospital disaster plans with national or regional emergency management systems. Programs that did not meet one or more of these criteria were classified as partial or non-comprehensive. The PICOS (Population, Intervention, Comparison, Outcome, and Study Design) framework guided the formulation of the research question and study selection, as it is well-suited for structuring systematic reviews that compare intervention outcomes across diverse healthcare settings. The population included hospitals located in earthquake-prone regions of the Middle East, ensuring the study remains focused on the unique challenges faced by the region and the specific strategies employed for seismic risk reduction programs; the Intervention involved the implementation of comprehensive seismic risk reduction programs; the Comparison involved hospitals with partial or no such programs; and the Outcome was the functionality of hospitals post-earthquake. Studies published between 2009 and 2024, written in English, and employing cross-sectional studies, cohort studies, case-control studies, case reports, and randomized controlled trials were included.

Exclusion criteria encompassed studies that focused on hospitals outside of earthquake-prone regions, studies without accessible post-earthquake data, and studies that did not concentrate on healthcare facilities. Additionally, studies employing methodologies such as meta-analyses, systematic reviews, or narrative reviews were excluded.

Data extraction and analysis

Three independent reviewers participated in the screening process to ensure a rigorous selection process. Titles and abstracts were first evaluated using Rayyan software, which allowed for systematic sorting and selection.

Studies that did not meet the inclusion criteria were excluded at this initial stage. Full-text articles for potentially relevant studies were retrieved and reviewed for eligibility based on the predefined criteria.

Then, data was extracted using a standardized form (Appendix 2) specifically developed for this systematic review. The form captured critical study elements, including author and publication year, country of study, research aims, study design, methods and instruments used, and data analysis techniques. The data extraction process was meticulously documented using Microsoft Word, and the reviewers cross-checked all entries for accuracy and completeness. Any disagreements in data extraction were resolved through consensus among the reviewers.

For the analysis, a narrative synthesis approach was employed to systematically summarize and interpret the key findings from the five included studies, which directly assess the level of hospital functionality following a major earthquake in the Middle East. This approach was selected due to the diversity and variability among the studies, which examined different aspects of seismic risk reduction programs and reported various outcomes. Findings were organized into three core themes: hospital preparedness, resource allocation effectiveness, and continuity of care. These themes emerged inductively during the data synthesis process based on recurring patterns across the included studies. The narrative synthesis approach enabled a comprehensive analysis that captured each study's findings, exploring how each theme contributes to the overarching goal of understanding hospital functionality post-earthquake, allowing for comparisons across studies, and identifying common patterns and gaps related to preparedness, response, and functional resilience.

Results

A total of 254 records were identified through database searches. After removing 39 duplicates, 215 articles underwent title and abstract screening. Of these, 191 were excluded, and 24 full-text articles were assessed for eligibility. Nineteen were further excluded due to a lack of hospital-specific data, inappropriate study design (e.g., systematic reviews or commentaries), or publication outside the target timeframe. Ultimately, five studies were included in the final review. The study selection process is summarized in Fig. 1.

Quality assessment

The quality of the five included studies was thoroughly evaluated using appropriate validated tools tailored to their respective study designs. Three independent reviewers conducted the assessment to ensure impartiality, applying different quality appraisal tools: the Joanna Briggs Institute (JBI) checklist for cross-sectional studies, the Critical Appraisal Skills Programme (CASP) tool for case studies, and the Mixed Methods Appraisal Tool (MMAT) 2018 for mixed-methods studies. Each tool was selected to match the specific study design.

As detailed in Table 1, Studies 1, 3, and 4, which employed a cross-sectional design, were assessed using the JBI checklist. Study 2, a case study, was evaluated using both the JBI and CASP tools. Lastly, "Study 5, a mixed-methods study, was appraised with the MMAT 2018 tool and was rated as 'Qualified,' meaning it met most core criteria but showed methodological concerns, particularly regarding the clarity of its sampling strategy (Note: 'Qualified' is not an official MMAT rating but a descriptive summary of the appraisal outcome). While it met most of the MMAT criteria, some concerns were raised regarding the clarity of its sampling strategy, which was identified as an area for improvement. Any discrepancies in the quality assessments were resolved through discussion among the reviewers.

Characteristics of the included studies

The five studies included in this review examine various strategies aimed at reducing seismic risk in hospitals across the Middle East, with study designs tailored to address region-specific needs. Three cross-sectional studies assessed hospital preparedness in Lebanon, Damghan, and Iran.

Al-Hajj et al. conducted a comprehensive assessment of 24 hospitals in Lebanon using a specialized Hospital Disaster and Emergency Preparedness (HDEP) tool, developed through expert input in a Delphi process [10]. The results indicated that while all hospitals had preparedness plans, significant gaps remained in recovery planning (83% lacked formal plans) and surge capacity (only 62% of hospitals had adequate coverage).

In Damghan, Iran, Pourmohammadi et al. evaluated 11 hospitals using the Hospital Safety Index and an emergency preparedness checklist [8]. Their findings revealed substantial deficiencies in structural safety (31.6% compliance) and operational readiness (49.3% preparedness), highlighting critical weaknesses in hospital service delivery during an earthquake.

Shakib et al. conducted a mixed-methods case study in Tehran, employing an exploratory sequential design that integrated qualitative data from local policymakers and quantitative assessments through a checklist [5]. The study underscored the importance of government commitment and public engagement in strengthening hospital resilience. It also identified gaps in the regular assessment of seismic risks and the need for ongoing structural upgrades.

Acar and Kaya utilized a two-stage stochastic model to assess the effectiveness of mobile hospitals in Istanbul,

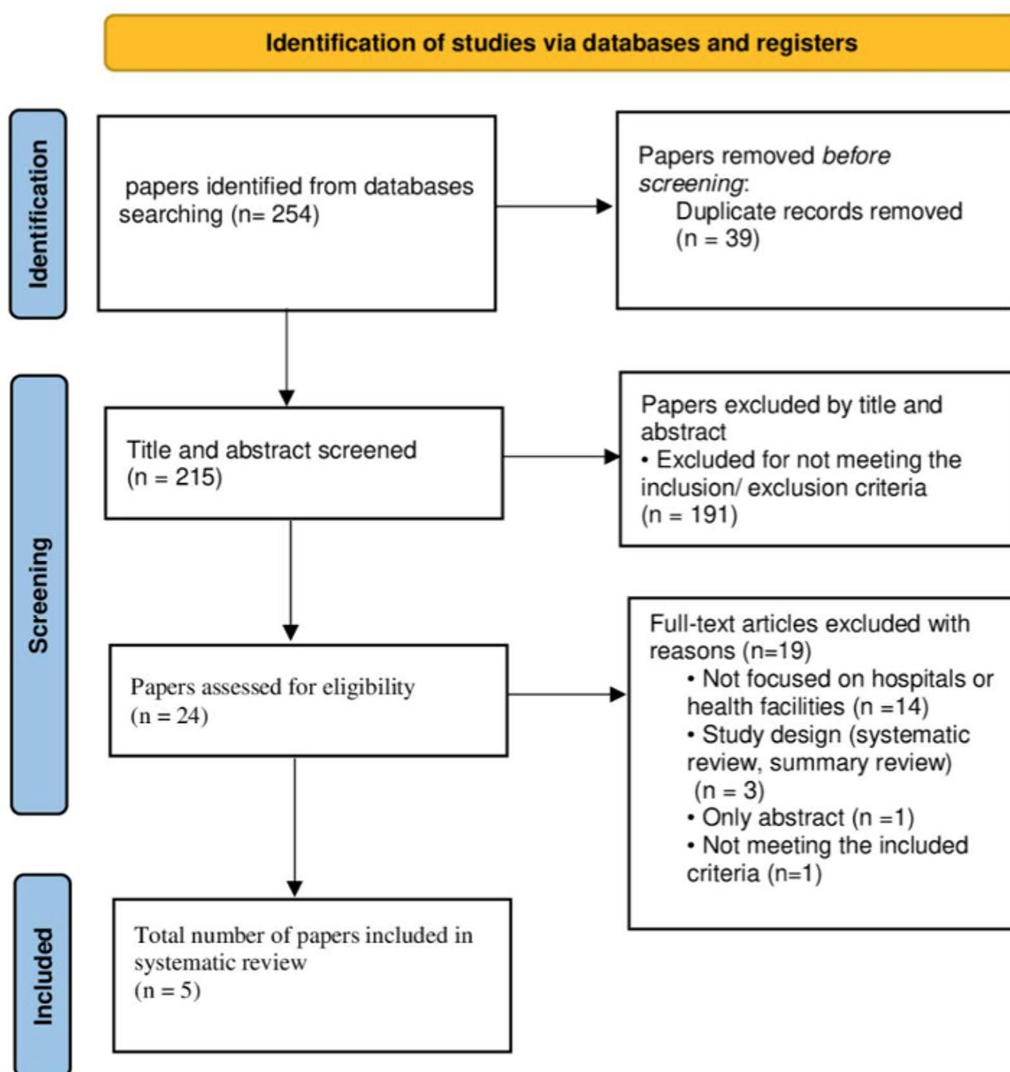

Fig. 1 Selection of studies for inclusion in the systematic review according to PRISMA Guidelines [11]

employing an embedded single-case research method [12]. The study found that mobile hospitals significantly reduced patient waits times and improved medical responses during seismic events, demonstrating the potential utility of mobile facilities in high-density, seismically active areas.

Together, these studies illustrate the strengths and weaknesses in hospital preparedness for seismic events in the Middle East. Notably, cross-sectional studies tended to report lower levels of structural preparedness and lacked longitudinal insight into implementation outcomes, highlighting the need for more robust, evaluative designs. They emphasize the importance of comprehensive seismic risk reduction strategies to maintain hospital operations. A summary of each study's design, objectives, and key outcomes is presented in Table 2.

Preparedness levels of hospitals

Hospitals in the Middle East exhibit varying levels of preparedness for seismic events. A study conducted in Lebanon revealed that all hospitals evaluated had formal emergency and disaster preparedness plans. However, only 79% of these hospitals routinely conducted disaster drills, and 62% had formal surge capacity plans [3]. In Iran, preparedness levels varied across medical facilities, with a survey in Damghan indicating an overall readiness of 45.8%. Structural safety compliance in these facilities ranged from 31.6 to 56.4%, pointing to widespread gaps in resilience [4]. Additional research in Iran found that while 86.7% of hospitals demonstrated good preparation, the mitigation of construction hazards remained inadequate, with only 56.6% of hospitals implementing necessary structural measures. The study defined satisfactory preparedness levels using a detailed questionnaire

Table 1 Methodological quality assessment of the reviewed studies by design-specific appraisal tools

Study ID	Study's Method	Tool	Quality Result	Justification
1. Al-Hajj, S., Abou-El-Hassan, H., Khalil, L., Kaafarani, H. M., & El Sayed, M. (2020). Hospital disaster and emergency preparedness (HDEP) in Lebanon: a national comprehensive assessment. International Journal of Disaster Risk Reduction, 51, 101,889	Cross section	JBI	Qualified	The criteria for inclusion and exclusion were clearly defined. The study subjects, including demographics, location, and time period described in detail. Moreover, the study clearly describes the method of measurement of exposure and there are a standard criterion used for measurement of the condition. The study used an appropriate statistical method.
2. Acar, M., & Kaya, O. (2019). A healthcare network design model with mobile hospitals for disaster preparedness: A case study for Istanbul earthquake. Transportation Research Part E: Logistics and Transportation Review, 130, 273–292	Case study	JBI, CASP	Qualified	It clearly states its aims, uses an appropriate study design, and employs sound methods for data collection and analysis. It shows significant findings on the effectiveness of mobile hospitals in disaster scenarios. While more detail on limitations and ethics is needed, the overall quality indicates its value for disaster preparedness.
3. Pourmohammadi, B., Heydari, A., Fatemi, F., & Modarresi, A. (2022). Assessing the preparedness of healthcare facilities for disasters and emergencies in Damghan, Iran. Disaster medicine and public health preparedness, 16(4), 1459–1465	Cross section	JBI	Qualified	Its clear objectives, appropriate study design, comprehensive methodology, and transparent presentation of results. The acknowledgment of limitations and ethical standards further strengthens its validity. The study provides valuable insights into the preparedness of healthcare facilities in Damghan, Iran, making it a useful resource for improving disaster readiness.
4. Shokouh, S. M. H., Anjomshoa, M., Mousavi, S. M., Sadeghifar, J., Armoun, B., Rezapour, A., & Arab, M. (2014). Prerequisites of preparedness against earthquake in hospital system: a survey from Iran. Global journal of health science, 6(2), 237	Cross section	JBI	Highly Qualified	The study meets the criteria for high quality based on its methodological rigor and clear findings.
5. Shakib, H., Joghan, S. D., & Pirizadeh, M. (2011). Proposed seismic risk reduction program for the megacity of Tehran, Iran. Natural Hazards Review, 12(3), 140–145	Mixed-method	MMAT 2018	Qualified	The study appears to meet most of the criteria assessed by the MMAT, including a robust mixed-methods approach, although the lack of clarity regarding the sampling strategy suggests a potential area for improvement.

covering eight dimensions, which were categorized as follows: (A) weak (0–49%); (B) moderate (50–74%); and (C) good (75–100%) [6].

In Lebanon, hospitals have prioritized staff training, yet there are still significant shortages in disaster-specific supplies and post-disaster mental health care. While training programs were reportedly implemented, the available studies did not provide sufficient evidence on whether these efforts translated into improved operational outcomes. For instance, following a crisis, only 15% of Lebanese hospitals offered mental health services. These findings indicate that while administrative preparedness is relatively robust, 100% of hospitals had disaster and emergency response plans, 83% included a recovery phase, and 62% had formal surge capacity plans, operational gaps remain, particularly in non-structural areas such as post-disaster psychological support and specialized disaster drills [3].

Effectiveness of resource allocation and mitigation measures

Various earthquake risk reduction techniques have been assessed in different regions, with structural reinforcements, such as building retrofits and enhanced compliance with national safety guidelines, being identified as essential but underutilized, for instance, in some regions Like Damghan, Iran, structural compliance was observed in only 31.6% of healthcare facilities, highlighting widespread implementation gaps. For example, only 31.6% of healthcare facilities in Damghan, Iran, met the structural preparedness standards, with significant gaps in compliance attributed to limited funding and insufficient enforcement of safety codes [5]. Similarly, Hosseini et al. reported that 86.7% of Iranian hospitals were generally prepared, but only 56.6% had adequately addressed construction hazard mitigation [9]. This discrepancy highlights barriers to the broader adoption of structural reinforcements, including financial constraints and a lack of regular seismic assessments [6].

Regulatory challenges hinder progress by directly affecting hospital functionality. In Tehran, although microzonation and seismic safety codes exist, enforcement is inconsistent. As a result, hospitals frequently bypass recommended upgrades, leaving critical infrastructure vulnerable. Bureaucratic delays further stall essential retrofitting projects, increasing the risk of operational failure during seismic events.

Table 2 Summary of included studies on hospital seismic preparedness

N	Title/Journal	Country	Aim	Design	Method/Instrument	Method of analysis	Key Findings
1	Hospital disaster and emergency preparedness (HDEP) in Lebanon: A national comprehensive assessment/International journal of Disaster Risk Reduction	Lebanon	Assess national hospital disaster and emergency preparedness	Cross-sectional assessment	HDEP tool, Delphi process, hospital assessments	Descriptive analysis, comparison of preparedness across regions	- All hospitals had plans, but 83% lacked recovery plans - 62% had surge capacity - 66.7% had backup communication - Only 25% had surgical ICUs - 15% offered post-disaster mental health services
2	A healthcare network design model with mobile hospitals for disaster preparedness: A case study for Istanbul earthquake/Transportation Research Part E: Logistics and Transportation Review	Turkey	Design mobile hospital network model for disaster preparedness	Case study	Two-stage stochastic model, queueing theory	Model-based analysis, optimization of resource allocation during disasters	- Mobile hospitals reduced wait times, improved access - Optimized healthcare resource allocation - Useful during high-impact disasters Like the 1999 İzmit earthquake
3	Assessing the Preparedness of Healthcare Facilities for Disasters and Emergencies in Damghan, Iran/Disaster Medicine and Public Health Preparedness	Iran	Assess hospital preparedness in Damghan	Cross-sectional study	Preparedness checklist with 272 items	Analysis of preparedness based on structural, functional, and nonstructural elements	- Overall preparedness 45.8% - Structural: 31.6%, Functional: 49.3%, Nonstructural: 56.4%
4	Prerequisites of Preparedness against Earthquake in Hospital System: A Survey from Iran/Global Journal of Health Science	Iran	Survey earthquake preparedness in Iranian hospitals	Cross-sectional study	Preparedness questionnaire (138 items, 8 dimensions)	Descriptive and comparative analysis of hospital preparedness based on 5management experience, bed occupancy rate	- Good overall preparedness (86.7%) - Weaknesses in construction hazard mitigation (56.6%)
5	Proposed Seismic Risk Reduction Program for the Megacity of Tehran, Iran/Natural Hazards Review	Iran	Propose seismic risk reduction for Tehran	Case study, mixed-methods	Seismic risk assessment, public/technical training programs	Analysis of risk reduction for urban structures, training effectiveness	- High seismic risk in Tehran - Major vulnerabilities in public infrastructure - Strategies: improved land use, training, insurance

Awareness and training gaps also contribute to the limited adoption of preparedness measures. Despite the initiation of public training programs, Pourmohammadi et al. observed that many hospital staff remain inadequately prepared for seismic events, Likely due to factors such as time constraints, Limited institutional support, and a lack of ongoing resources for practical training, with less than 50% of personnel participating in disaster preparedness drills [8]. This lack of awareness regarding the importance of regular training further hampers preparedness efforts, leaving hospitals vulnerable during disasters [5, 7].

In Turkey, mobile hospitals have been explored as a potential solution to the shortage of emergency healthcare capacity during seismic events. A two-stage stochastic model was used to demonstrate the effectiveness of mobile units in reducing response times. These mobile hospitals can be rapidly deployed to targeted areas, significantly decreasing the time required to deliver essential healthcare services [4]. In Istanbul, for example, simulation-based models and pilot deployments have demonstrated their potential to reduce patient wait times and alleviate pressure on fixed hospital infrastructure during seismic events.

In summary, while structural reinforcements and training programs offer significant potential to mitigate the impact of seismic events, inconsistent implementation and resource limitations severely undermine their effectiveness. Strengthening compliance mechanisms, increasing funding for retrofitting, and expanding public

awareness initiatives are crucial to the success of seismic risk reduction programs. These efforts should be led by national governments in collaboration with local health authorities, and supported by international organizations through technical assistance, funding, and policy guidance.

Continuity of hospital functionality

In Lebanon, all hospitals provided on-site pharmacies and essential medical supplies, including equipment, pharmaceuticals, power generators, water, and oxygen. However, only 66.7% were equipped with backup communication systems, posing a significant risk to the continuity of hospital operations during crises [3]. This lack could lead to delayed coordination among departments and emergency teams, disrupted patient tracking, and compromised communication with external response agencies. Studies conducted in Iran revealed structural weaknesses that hindered hospital functionality during earthquakes. In Damghan, 31.6% of healthcare facilities failed to meet structural preparedness standards, with critical components such as walls, ceilings, and support columns exhibiting vulnerabilities. This resulted in the evacuation of patients from affected units, which in turn disrupted access to critical care services, particularly in intensive care and surgical departments, increasing the risk of adverse patient outcomes. Additionally, 42% of hospitals reported ceiling damage, posing a risk of falling debris, leading to the closure of specific areas. Entire hospital wings had to be shut down to ensure patient and staff safety, disrupting essential services, including intensive care and surgical procedures. Furthermore, embedded infrastructure, such as electrical cables and water pipes, sustained damage, leading to 50% of hospitals losing electricity during crises, and 37% encountering water supply disruptions. These issues significantly affected the delivery of essential services [5]. In some cases, destroyed infrastructure caused the loss of specialized medical equipment, forcing hospitals to rely on backup units or transfer patients to the nearest facilities [6].

Tehran's earthquake risk-reduction strategy includes microzonation and seismic safety code compliance to enhance the resilience of healthcare facilities. Microzonation divides the city into 13 seismic zones based on geological features and seismic risks. This approach guides the identification of safer sites for medical centers and directs retrofitting activities in high-risk zones. Facilities located in safer zones are less Likely to be disrupted by earthquakes, ensuring uninterrupted healthcare services. Moreover, hospitals in high-risk areas benefit from priority upgrades to improve their earthquake resistance. Despite these efforts, 31.6% of Tehran's healthcare facilities remain non-compliant with seismic safety codes, making them more susceptible to structural damage. Non-compliant hospitals experienced 50% power outages and 37% water supply issues during past earthquakes, directly affecting patient care. While specific durations were not always reported, these disruptions likely ranged from temporary service interruptions to partial shutdowns in critical departments, depending on the availability of emergency backup systems. In contrast, compliant hospitals equipped with backup generators and water storage systems were able to continue operations with minimal disruption, reducing the need for patient evacuations. These measures ensure the continuous provision of care, prevent evacuations, and reduce operational interruptions during seismic events. Expanding compliance with seismic safety codes and updating facilities based on microzonation guidelines are crucial for maintaining healthcare operations in earthquake-prone regions [7]. These efforts should be led by national ministries of health in partnership with municipal governments and urban planning authorities, who are best positioned to enforce building standards and prioritize healthcare infrastructure upgrades.

Mobile hospitals have proven to be a cost-effective and operationally efficient solution for enhancing healthcare resilience, particularly in regions Like Turkey, where 13 out of 48 hospitals faced significant overload risks. Mobile units reduced response times by 30%, avoided 40% of patient transfers, and shortened transport times by 15%, resulting in a reduction in wait times from 3.5 to 2.8 h during events such as the Marmara Sea earthquake. The Mobile Hospital Life-Cycle Assessment (MHLCA) model outperformed the Conventional and Simplified Hospital Life-Cycle Assessment models, reducing costs by 10.4%, compared to the 12.3% and 10.4% increases observed in the other models. Mobile units successfully redistributed 35% of patient demand from overcrowded hospitals, balancing workloads and ensuring continuous care. Their flexibility and cost-efficiency play a critical role in maintaining operational stability and enhancing the resilience of healthcare systems during disasters [4].

Discussion

This review contributes to the growing body of literature on disaster risk reduction by offering one of the first regional syntheses focused exclusively on hospital functionality during seismic events in the Middle East. It systematically evaluates the effectiveness of comprehensive seismic risk reduction programs in maintaining hospital functionality in earthquake-prone areas across the region. Given the region's complex risk landscape, marked by high seismicity, political instability, and limited health system resources, the findings carry broader implications for other low- and middle-income settings facing similar constraints [13]. Understanding how structural, operational, and governance-related interventions

interact in real-world hospital settings is critical to designing scalable, evidence-informed strategies for disaster resilience. The findings reveal considerable disparities in hospital preparedness across the region, highlighting both strengths and persistent gaps in structural, operational, and policy-related dimensions.

Hospital preparedness for seismic events varies significantly between countries in the Middle East. For example, while Lebanon demonstrates relatively strong administrative preparedness, operational gaps persist [3]. Only 79% of hospitals conduct regular disaster drills, and just 62% have surge capacity plans, likely due to constraints such as limited budgets, competing administrative priorities, and lack of formal policies mandating these practices. This indicates that many facilities may struggle to maintain operations during large-scale disasters, potentially experiencing breakdowns in triage systems, interruptions in ICU or surgical care, and failures in emergency communication and logistics coordination.

A critical comparison of these country-specific findings suggests that structural resilience tends to be prioritized in settings where governmental enforcement of building codes is strong (e.g., Tehran), whereas functional preparedness measures, such as surge capacity planning and communication protocols, are more consistent in politically stable, higher-income contexts (e.g., Lebanon). These patterns highlight that resilience outcomes are shaped not only by financial investment but also by governance structures, regulatory enforcement, and interagency collaboration. In some cases, higher preparedness scores may reflect narrow measurement tools that overemphasize administrative protocols without fully capturing operational readiness during crisis conditions. This divergence in assessment criteria complicates cross-country comparisons and underscores the need for harmonized evaluation frameworks. At the same time, direct comparisons across studies should be approached cautiously, as variability in preparedness scores often stems from methodological differences, including divergent assessment tools, inconsistent operational definitions, and varying emphasis on structural versus functional domains. For example, some high-scoring facilities may appear well-prepared on paper yet lack tested surge capacity or redundancy in critical systems, limiting real-world resilience. Conversely, lower-scoring hospitals in certain assessments may in fact maintain operational continuity through informal networks or adaptive resource management not captured by standardized tools. This heterogeneity complicates meta-analysis and underscores the urgent need for harmonized evaluation criteria across the region.

In Iran, the situation is more concerning. Only 45.8% of hospitals meet overall preparedness standards, and 31.6% do not satisfy seismic safety criteria. This structural vulnerability stems from inadequate infrastructure investment and insufficient enforcement of safety codes. These findings highlight critical resource and policy enforcement gaps that limit healthcare system resilience in the region [4].

The review emphasizes the importance of both structural resilience and operational readiness in maintaining hospital functionality. For instance, in Damghan (Iran), many hospitals with poor seismic safety suffered structural damage leading to evacuations and service interruptions. Conversely, hospitals in Tehran that adhered to seismic safety standards experienced fewer disruptions, underlining the impact of enforcement and investment in structural upgrades [4]. This adherence may be attributed to local government initiatives that prioritized retrofitting based on seismic microzonation data, as well as active leadership by hospital administrators committed to maintaining disaster readiness.

Similarly, hospitals in Lebanon that maintained essential medical supplies and power backups still struggled due to the absence of communication systems, 66.7% lacked backup communication [3]. This shows that nonstructural operational elements are also critical to sustaining hospital services during earthquakes.

An important consideration is the limited integration of hospital preparedness efforts into broader national emergency management systems. Many of the reviewed hospitals operated in silos, with weak or ad hoc coordination mechanisms with civil defense, public health agencies, and logistics partners. Without strong cross-sectoral planning, even structurally sound hospitals can face breakdowns in staffing, supply chains, and patient transfers during a seismic crisis [14]. A more integrated, systems-based approach to risk reduction is needed, including formal inter-agency protocols and joint simulation exercises.

Political instability and armed conflict in parts of the Middle East further complicate the implementation of seismic risk reduction programs [15]. In fragile states or conflict zones, hospitals often operate under chronic resource constraints, security threats, and fragmented governance, making sustained investment in infrastructure or training infeasible. Future frameworks for hospital resilience should account for these constraints and promote flexible, conflict-sensitive approaches to risk reduction [16]– [17].

Across the studies reviewed, hospitals with comprehensive seismic risk reduction programs generally demonstrated better preparedness and functionality. These programs often include building retrofits, regular drills, surge capacity planning, and emergency communication protocols, all of which require sustained financial investment, strong governance frameworks, and effective institutional coordination to implement and maintain over

time. While the evidence strongly supports the value of such programs, there remains a lack of direct, comparative studies evaluating functionality outcomes between hospitals with full, partial, or no risk reduction programs. Future research could benefit from measuring metrics such as patient throughput, duration of service interruption, speed of infrastructure recovery, and mortality or complication rates post-disaster to establish clearer comparisons. This represents a key limitation in the existing literature. A useful approach to address this gap could be a multi-country comparative cohort study assessing hospital outcomes post-earthquake, using standardized indicators such as time to operational recovery, patient volume throughput, and rates of critical service disruption. This would provide concrete evidence on the effectiveness of different levels of seismic preparedness.

Equally important is the institutional culture of preparedness. Several facilities reported having protocols or equipment in place but lacked regular training, follow-up, or staff engagement. Without consistent simulation drills and leadership support, these programs risk becoming superficial. Embedding risk reduction into routine hospital operations, rather than as an occasional checklist, may help develop a sustainable "culture of readiness," particularly in medium-sized or rural hospitals where turnover is high and disaster risk is underestimated [18].

Some studies explored the use of innovative strategies such as mobile hospitals to support overloaded facilities during disasters [19]. In Turkey, mobile units reduced response times by 30%, minimized patient transfers by 40%, and decreased transport times by 15%. These findings point to the potential of mobile healthcare units as a flexible, cost-effective solution for maintaining hospital functionality during seismic events. However, widespread implementation remains limited in the Middle East.

Although mobile units are promising, they also face practical constraints. Their deployment requires advanced logistical planning, integration into emergency response networks, and ongoing maintenance, which may pose challenges for underfunded or fragmented health systems. Furthermore, their success depends on the capacity to staff them adequately during crises, a factor often overlooked in modeling studies. Therefore, mobile hospitals should be positioned as complementary assets within broader national disaster frameworks, rather than standalone [20].

Finally, the absence of a standardized set of metrics across the studies complicates regional benchmarking and policymaking. Indicators such as average time to service restoration, critical care downtime, patient rerouting frequency, or even surgical throughput under crisis conditions could serve as common tools for future comparisons. The development of such indicators, ideally under the guidance of WHO or a regional health body, could enhance evidence-based decision-making and resource allocation in seismic preparedness.

Despite growing recognition of the importance of hospital resilience, most countries in the region lack comprehensive regulatory frameworks mandating seismic retrofitting, regular drills, or functional integration with national disaster management plans [21]. In several cases, hospitals are excluded from urban resilience strategies, and national health policies do not prioritize structural safety or continuity planning [22]– [23]. These policy and governance gaps are compounded by fragmented funding mechanisms and the absence of long-term investment planning, leaving hospitals vulnerable in both urban and rural areas.

Taken together, the reviewed evidence underscores that improving hospital functionality in seismic settings requires more than isolated technical upgrades, it demands an integrated, multisectoral approach. Policymakers should prioritize national frameworks that align seismic retrofitting with operational planning, training programs, and emergency logistics. Funding strategies must be tailored to local contexts, especially in under-resourced rural areas, where vulnerability is often highest. Strengthening hospital resilience is not solely a technical or engineering issue, but a strategic imperative for public health systems.

These findings also resonate with the principles set out in the WHO Safe Hospitals Framework and FEMA 396 guidelines, both of which emphasize the integration of structural safety, functional continuity, and governance mechanisms into hospital disaster preparedness. While the reviewed programs broadly align with these international standards, our synthesis indicates that implementation in the Middle East is often partial, with governance and inter-agency coordination lagging behind structural measures. This highlights the need for adaptation of these frameworks to account for the region's political, economic, and infrastructural realities, ensuring that global benchmarks translate into feasible, context-specific actions.

Future research should prioritize the development and validation of standardized, context-sensitive metrics for hospital seismic resilience, capturing both structural performance and functional continuity under real crisis conditions. Multi-country prospective cohort studies, using common outcome measures such as time to operational recovery, duration of critical service interruption, and patient outcomes, would provide the comparative evidence base currently missing from the literature. Such studies should also integrate qualitative assessments of governance, leadership, and inter-agency coordination, which remain underexplored yet critically influence hospital performance during disasters. This review provides a foundation for developing targeted interventions,

informed policies, and measurable performance indicators that can enhance disaster readiness in hospital systems across the Middle East and comparable settings worldwide.

Limitations and directions for future research

While this review identifies trends supporting the effectiveness of comprehensive seismic risk reduction programs, several limitations must be acknowledged. First, the conclusions regarding hospital functionality are based on comparisons across heterogeneous studies rather than on direct measurements. The included studies varied in how they defined and assessed "preparedness," with some emphasizing structural integrity while others focused on administrative planning or staff training. This methodological variability limits the direct comparability of findings.

Moreover, there is a potential for publication bias, as the review included only peer-reviewed articles published in English. Most studies originated from a small number of countries, primarily Iran, Turkey, and Lebanon, while high-risk regions such as Syria, Iraq, and Jordan remain underrepresented. This geographic skewness may limit the generalizability of the conclusions and obscure regional challenges in implementing effective seismic risk reduction strategies.

Future research should prioritize study designs that enable more direct and comparable measurements of hospital functionality outcomes. Prospective multicenter cohort studies and simulation-based evaluations using standardized disaster scenarios could provide more robust evidence. It would also be valuable to conduct economic evaluations of mitigation strategies to assess cost-effectiveness and support investment decisions.

Additionally, further evaluation of adaptive strategies beyond mobile hospitals, such as modular field units, telemedicine hubs, or mobile command centers, may offer new solutions for strengthening healthcare resilience. However, these approaches should also be critically examined for feasibility, cost, and integration with existing systems.

Finally, there is a pressing need to adopt standardized metrics to evaluate hospital performance during and after earthquakes. Relevant indicators might include operational downtime, average patient wait time, speed of service restoration, patient throughput during surge periods, and the duration of critical service disruptions. Developing and applying such metrics across diverse settings would help generate more actionable, policy-relevant evidence and guide strategic planning in earthquake-prone regions.

Conclusion

Hospitals in the Middle East demonstrate foundational efforts toward seismic preparedness, yet major deficiencies persist in structural safety, operational readiness, and adaptive capacity. This review affirms that comprehensive seismic risk reduction programs, those integrating structural retrofitting, coordinated drills, emergency supply planning, and communication protocols, are linked to improved hospital functionality during and after earthquakes.

A centralized funding mechanism led by national health ministries and supported by municipal authorities could serve as a high-impact intervention to address structural and operational gaps simultaneously. Such funding should prioritize high-risk zones identified through microzonation, and support regular simulation-based drills aligned with hospital emergency plans.

To advance evidence-based policymaking, future research should focus on longitudinal assessments of hospital performance post-disaster, simulation modeling under varying resource constraints, and economic evaluations of mitigation strategies. Moreover, comparative cohort studies using standardized functionality metrics, such as operational downtime, surge capacity performance, or speed of service restoration, would strengthen the evidence base for scalable investments in hospital resilience across the region. Lessons learned from the Middle East context may also inform preparedness strategies in other low- and middle-income countries facing similar seismic risks and health system constraints.

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

Authors' contributions

Conceptualization: YA, MA, AA, THMethodology: AH, YA, RA, AALiterature Search: EA, AS, RR, MSScreening and Selection of Studies: AH, AS, EA, YAData Extraction: TH, RA, AA, MS, Quality Appraisal: MA, AA, RR, EAData Analysis and Interpretation: YA, RA, MS, EA, AAWriting – Original Draft Preparation: TH, AH, RA, AA, EA, AS, RR, Writing – Review and Editing: YA, MA, AA, MSSupervision: YA, MA, AA, MSProject Administration: RA, TH, AH, AS.

Data availability

No datasets were generated or analysed during the current study.

Declarations

Competing interests

The authors declare no competing interests.

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