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Corresponding author:
Hassan Farhat, PhD
Email: hassen.farhat@gmail.com

Preparedness and Response Strategies for Chemical, Biological, Radiological, and Nuclear Incidents in the Middle East and North Africa: An Artificial Intelligence-Enhanced Delphi Approach

Hassan Farhat PhD[1,2,3], Guillaume Alinier PhD[1,4,5,6], Nidaa Bajow MD[7], Alan Batt PhD[8,9], Mariana Charbel Helou MD[10,11], Craig Campbell PhD[12], Heejun Shin MD[13,14,15,16], Luc Mortelmans MD[17,18,19], Arezoo Dehghani PhD[20,21], Carolyn Dumbeck MSc[22], Roberto Mugavero MD[23,24,25], Walid Abougalala MBBS[26], Saida Zelfani MD[26,27], James Laughton MBBS[1], Gregory Ciottone MD[16,28] and Mohamed Ben Dhiab MD[1]

[1]Ambulance Service, Hamad Medical Corporation, Doha, Qatar; [2]Faculty of Medicine "Ibn El Jazzar," University of Sousse, Sousse, Tunisia; [3]Faculty of Sciences, University of Sfax, Sfax, Tunisia; [4]School of Health and Social Work, University of Hertfordshire, Hatfield, UK; [5]Weill Cornell Medicine-Qatar, Doha, Qatar; [6]Faculty of Health and Life Sciences, Northumbria University, Newcastle upon Tyne, UK; [7]Security Forces Hospital, Riyadh, Saudi Arabia; [8]Queen's University, Ontario, Canada; [9]Monash University, Melbourne, Australia; [10]School of Medicine, Lebanese American University, Beirut, Lebanon; [11]Lebanese American University-Rizk Hospital, Beirut, Lebanon; [12]School of Paramedicine, University of Tasmania, Tasmania, Australia; [13]Soonchunhyang Disaster Medicine Center, Seoul, South Korea; [14]Soonchunhyang University Bucheon Hospital, Seoul, South Korea; [15]Shin's Disaster Medicine Academy, Seoul, South Korea; [16]Harvard Medical School, Harvard University, Boston, MA, USA; [17]European Society for Emergency Medicine, Antwerp, Belgium; [18]Catholic University of Leuven, Leuven, Belgium; [19]Free University Brussels, Brussels, Belgium; [20]Safety Promotion and Injury Prevention Research Center, Shahid Beheshti University of Medical Sciences, Tehran, Iran; [21]Health in Disasters and Emergencies Research Center, Institute for Futures Studies in Health, Kerman University of Medical Sciences, Kerman, Iran; [22]Alberta Health Services, Alberta, Canada; [23]University of Rome "Tor Vergata," Department of Electronic Engineering, Rome, Italy; [24]University of the Republic of San Marino, Centre for Security Studies; [25]Observatory on Security and CBRNe Defense, Rome, Italy; [26]SAMU 01 North East, Ministry of Health, Tunis, Tunisia; [27]Faculty of Medicine, University of Tunis El Manar, Tunis, Tunisia and [28]Harvard T.H. Chan School of Public Health, Boston, MA, USA

Abstract

Objective: Chemical, biological, radiological, and nuclear (CBRN) incidents require meticulous preparedness, particularly in the Middle East and North Africa (MENA) region. This study evaluated CBRN response operational flowcharts, tabletop training scenarios methods, and a health sector preparedness assessment tool specific to the MENA region.

Methods: An online Delphi survey engaging international disaster medicine experts was conducted. Content validity indices (CVIs) were used to validate the items. Consensus metrics, including interquartile ranges (IQRs) and Kendall's W coefficient, were utilized to assess the panelists' agreement levels. Advanced artificial intelligence computing methods, including sentiment analysis and machine-learning methods (t-distributed stochastic neighbor embedding [t-SNE] and k-means), were used to cluster the consensus data.

Results: Forty experts participated in this study. The item-level CVIs for the CBRN response flowcharts, preparedness assessment tool, and tabletop scenarios were 0.96, 0.85, and 0.84, respectively, indicating strong content validity. Consensus analysis demonstrated an IQR of 0 for most items and a strong Kendall's W coefficient, indicating a high level of agreement among the panelists. The t-SNE and k-means identified four clusters with greater European response engagement.

Conclusions: This study validated essential CBRN preparedness and response tools using broad expert consensus, demonstrating their applicability across different geographic areas.

Recent global events have revealed an escalating risk of chemical, biological, radiological, and nuclear (CBRN) incidents, necessitating an urgent focus on health sector preparedness worldwide.[1-6] The potential manipulation of viruses and other materials into biological or chemical weapons presents an undeniable global threat, as observed in past incidents involving Sarin, Mustard gas, and the Novichok agent.[7-9] Despite being deployed to target specific individuals, these agents have resulted in numerous unintended casualties, demonstrating the far-reaching consequences of biological threats.

A worldwide consensus exists regarding the urgency of enhancing national CBRN preparedness, particularly in regions marked by complicated geopolitical conflicts, such as the Middle East and North Africa (MENA) region. Furthermore, this region is characterized by its fragile infrastructure, such as Tunisia and Egypt, which amplifies the challenges of ensuring adequate disaster management.

Notable efforts to empower health-care professionals to manage CBRN incidents have been conducted in various MENA countries.[10-12] However, these initiatives are often dispersed and independently conducted in each country, which may dilute their long-term impacts and threaten sustainability. Considering the transnational nature of CBRN threats, adopting collaborative approaches that address the extensive nature of such incidents and mitigate the financial and logistical disparities across the MENA region is imperative. This involves formulating adaptable strategies to minimize the threat of CBRN incidents on neighboring and concerned nations. Recent developments within European networks, such as the "European Network of CBRN Training Centers," have only highlighted MENA countries' need to consolidate their efforts in training and planning for CBRN incidents using various approaches, including full-scale exercises and virtual, augmented, and mixed reality simulations.[2,13-15] In contrast to Europe's linguistic diversity, this integration is arguably more attainable within the MENA region, where individuals share a common native language and cultural norms alongside similar internal or external threats.

Advancing this unification necessitates modernizing policies and strategies for continuous improvement; however, no published study has proposed a prototype for a unified health-care readiness checklist or cohesive training and response guidelines for CBRN incidents across the MENA region. Such initiatives could catalyze the path toward policy improvement.

Therefore, this study aimed to develop a region-specific assessment tool, operational response guidelines for managing CBRN incidents in the MENA region, and simulation tabletop exercises for training pre- and in-hospital health-care professionals.

Methods

Study Design

This cross-sectional mix method study was approved by the Ethical Committees of the Faculty of Medicine "Ibn Eljazzar" of Sousse in Tunisia and of the Hamad Medical Corporation's Medical Research Center in Qatar (under references CEFMS 110/2022 and MRC-01-22-258, respectively). This study used the online Delphi method rather than a regular survey owing to the former's ability to harness collective expert opinions from a dispersed group and reach a consensus among an expert panel, ensuring a more robust and informed assessment tool suitable for the specific complexities and nuances of CBRN preparedness and responses in the health sector in the MENA region.

The study comprised four phases: 1) a systematic review, 2) an initial qualitative Delphi phase, 3) a Delphi tools design and validation process, and 4) experts' recruitment.

Phase 1: A systematic literature review

A systematic literature review (SLR) was conducted and registered in PROSPERO (ID: CRD42022372815).[16] This review employed the search strategy outlined in Appendix 1 and included articles published until the initiation of this study. The SLR aimed to identify and define strategies adopted by health-care sectors globally, not just within the MENA region, to improve preparedness for CBRN incidents.

Phase 2: Initial qualitative Delphi

Published resources on the preparedness of MENA countries for CBRN incidents are lacking; thus, a qualitative phase was deemed necessary to supplement the limited information available in the existing literature. In this phase, participants were asked open-ended questions to obtain their perspectives on the topic and identify the most relevant elements for enhancing the preparedness and response levels of the MENA health sector regarding potential CBRN incidents. This approach provided a more comprehensive understanding of the situation, which existing publications could not fully capture. A unanimous agreement existed regarding the need for MENA countries to cooperate in ensuring adequate health-care preparedness for CBRN threats.[17] Moreover, various gaps were highlighted, such as inadequacies in national practices and policies, the necessity for international cooperation, and the ineffectiveness of current hospital preparedness measures. The findings of this preliminary qualitative phase have been discussed in previous publications.[16-18]

Phase 3: Delphi questionnaire design and validation process

The questionnaire was designed using the outcomes from the systematic review and the qualitative phases.

Researchers with expertise in disaster management, particularly CBRN incident management, were invited to validate the Delphi survey online. The questions were uploaded to the Phonic® platform. The Delphi survey questions were divided into two parts: 1) CBRN response flowcharts (https://rb.gy/01ez1o) and the suggested simulation tabletop exercise training scenarios (https://rb.gy/2xa4gv) and 2) health-care sectors' readiness assessment for CBRN incidents. Validators were instructed to validate each question separately as they had different objectives. They were requested to score the questions' clarity to the reader and relevance to the objectives, with 1 indicating the lowest score and 5 indicating the best score. Furthermore, the validators were instructed to provide audio-recorded or written free-text feedback for each question.

Phase 4: Experts' recruitment

In this study, sampling was done purposefully. Individuals representing the MENA countries were selected based on their background in disaster medicine, their roles in their institutions, a keen interest in the preparedness of the MENA region for CBRN incidents, and the co-authors' network. This targeted recruitment ensured that the panel comprised professionals with relevant experience and a deep understanding of the regional challenges and disaster management requirements. Their collective expertise was essential in developing a preparedness assessment tool, operational response flowcharts, and simulation tabletop exercises for training that were relevant and informed by the latest practices in the field.

Data Collection, Measurement, and Variables

Data collection was conducted using the Phonic® online platform, which features automatic response saving. This functionality permits pausing and resuming at the final completion point, facilitating experts' participation without impinging on their other commitments. A 5-point Likert scale was adopted to quantitatively evaluate specific variables relevant to the study's objectives. The scale ranged from "Extremely Agree" to "Extremely Disagree," with "Agree," "Unsure," and "Disagree" as the intermediate options. Demographic variables were included at the outset of the Delphi questionnaire.

For the first part of the Delphi questionnaire that focused on the development of a preparedness assessment tool, the following measured variables were included: 1) medical protocols and logistics; 2) infrastructure readiness for CBRN incidents in the MENA region; 3) decontamination capabilities; 4) specialized human resources capabilities; 5) public health, national practice, prevention, preparedness, policies, and interregional coordination; 6) research and development; 7) psychological support; 8) post-incident recovery and rehabilitation; 9) interagency cooperation and coordination; and 10) legal and ethical considerations. Each variable was meticulously designed to reflect the intricate and multidimensional aspects of CBRN incident management. The second part of the Delphi questionnaire focused on establishing operational response flowcharts and simulation tabletop exercises for training pre- and in-hospital health-care professionals. The practicability and efficacy of various response strategies and training scenarios were examined using the following variables: safety protocols, triage, decontamination, symptom management, and treatment protocols. The complete set of questions can be accessed using the following link: https://survey.phonic.ai/6575c9fda6c6b22db1d52e44?preview=true).

An Artificial Intelligence (AI)-Enhanced Statistical Analysis Process

R programming language using the R-Studio™ environment (R Foundation for Statistical Computing, Vienna, Austria) was used to conduct statistical analysis, including validation and the Delphi questionnaire outcome.

Analysis of the validation results

The content validity index (CVI) was used to assess item validity. The CVI is advantageous in validating survey instruments because it considers the extent of agreement among expert raters and the significance of each rating. The item-level CVI (I-CVI) for each question and the scale-level CVI (S-CVI) were used to measure the validity of each item as perceived by the expert panel and the overall validity of the scale, respectively.

Furthermore, sentiment analysis, an AI computing method, was employed to evaluate qualitative feedback from the expert panel. A code was generated in R-Studio™ to determine the validators' sentiment scores when writing open-ended feedback for each question in the text box underneath. Further sentiment analysis was performed for the validator's open-ended feedback on each question to understand the experts' perceptions beyond numerical ratings. The sentiment analysis method employed a lexicon-based approach to classify text into various sentiment categories, such as positive, negative, and neutral. For example, during the initial wave of the COVID-19 pandemic, sentiment analysis was utilized to sort patient feedback into positive and negative sentiments, thereby identifying areas for quality improvement in emergency care.[19] Similarly, during Hurricane Sandy, sentiment analysis of social media data was crucial in understanding public emotions and informing emergency response strategies.[20] Further, an analysis of variance (ANOVA) was conducted to examine the influence on sentiment scoring. The objective was to determine whether the differences in sentiment scoring were due to the characteristics of the items, sentiment types, or variability among the validators' judgments, which provided statistical evidence to confirm the consistency of ratings across validators, ensuring that the sentiment scores were reliable and not biased by individual perceptions.

Analysis of the Delphi survey outcomes

First, descriptive statistics were used to ascertain the central tendency and variability of the responses for each item and provide an overview of the data distribution. This involved the determination of the mean, median, and standard deviation for each question. Second, agreement analysis was performed by determining the mode to identify the most common response per item and calculating the percentage agreement, focusing on the proportion of respondents who selected the top two options ("Agree" and "Strongly Agree"). Third, consensus was measured through agreement percentages, medians, interquartile ranges (IQRs), standard deviation (SD), and the Kendall W coefficient of concordance, a non-parametric measure used to determine the agreement among judges. Its value ranges between 0 and 1.[21] The closer it is to one, the stronger the agreement is. Finally, clustering analysis was performed using t-distributed stochastic neighbor embedding (t-SNE) and k-means clustering, which constitute AI-unsupervised machine-learning methodology functions with data-driven groupings and pattern recognition elements that enhance the interpretability of clustering results, allowing high-dimensional group representation. The t-SNE was applied to reduce the dimensionality of the data, making it easier to visualize high-dimensional patterns. At the same time, k-means clustering was used to identify natural groupings within the data. These AI techniques enhanced the understanding of consensus patterns and the robustness and interpretability of the Delphi survey outcomes. Previously published research used t-SNE to analyze gene expression data and clinical metadata, which helped identify consensus clusters and understand patient attributes more precisely.[22] Further, during the COVID-19 pandemic, k-means clustering was applied to categorize patients based on their symptoms and outcomes, helping to identify patterns that could predict recovery or mortality. This clustering approach helped explore the characteristics of patients who were more likely to recover versus those at higher risk of death, thereby informing targeted medical interventions.[23]

Results

This study included 40 multidisciplinary, international experts specializing in disaster and CBRN emergency management who participated in the online Delphi survey from November 1, 2023, to January 30, 2024. The average completion time was 36.24 min.

Demographic Data

The demographic analysis (Table 1) revealed a mean age of 46.2 (SD = 9.31, median = 45.5, IQR = 16.2) years and an average professional experience time of 13.6 (SD = 8.98, median = 11.5, IQR = 12.8) years. Regarding sex distribution, the panel constituted 16 females (40%), 20 males (50%), and 4 participants who preferred not to disclose their gender (10%). The panelists represented a diverse geographical background, with the majority from Tunisia (15%), Saudi Arabia (12.5%), France (10%), Belgium, Lebanon, and Qatar (7.5% each), whereas smaller representations were from Egypt, Iran, and Portugal (5% each), and 1 participant from Canada. The experts were affiliated with various internationally recognized institutions, including the International Institute of CBRN.

Validation Results

The CBRN response flowchart, the tabletop scenarios, and the preparedness assessment tool were validated separately (Table 2).

Table 1. Demographic information of the Delphi process experts

I) Continuous variables				
	Mean	Median	SD	IQR
Age	46.20	45.50	9.31	16.20
Experience	13.60	11.50	8.98	12.80

II) Categorical variables		
Gender	Count	Percent (%)
Female	16	40
Male	20	50
Prefer not to disclose	4	10
Country	Count	Percent (%)
Tunisia	6	15
Saudi Arabia	5	12.5
France	4	10
Belgium	3	7.50
Lebanon	3	7.50
Qatar	3	7.50
Egypt	2	5
Prefer not to disclose	2	5
Iran	2	5
Portugal	2	5
Canada	1	2.50
Kuwait	1	2.50
Morocco	1	2.50
Palestine	1	2.50
South Korea	1	2.50
Turkey	1	2.50
UAE	1	2.50

The I-CVIs for the CBRN preparedness assessment tool, response flowchart, and tabletop scenarios were 0.96, 0.85, and 0.84, respectively, indicating strong content validity of the Delphi survey tools.

The negative values of the Kappa and ICC coefficients for both tools indicated challenges in obtaining similar agreement between the validators for each item of the tools, leading them to provide open-ended feedback.

An AI-based sentiment analysis of the validator feedback was conducted. The heatmap in Figure 1 illustrates the sentiment scores categorized by sentiment type from multiple open-ended feedback across a range of items, providing insight into the evaluative criteria used by the validators. Diverse scoring patterns were identified. "Positive" sentiments generally received higher scores, whereas "mixed" sentiments showed a more varied distribution of scores. "Negative" sentiments consistently received lower scores, whereas "neutral" sentiments displayed a moderate scoring pattern. The consistency across the validators for each sentiment type suggests a coherent scoring approach that was not identified using Kappa and ICC coefficients. Appendix 2 provides the detailed results of the validation process.

Table 2. Validity of the tools utilized for the Delphi Survey

1. Content validity coefficients analysis						
1.1 Flowcharts						
ICVI	CI_Lower	CI_Upper	Kappa	SCVI_Avg	SCVI_Prop	ICC
0.84	0.34	0.94	−0.31	0.85	0.66	−0.07
1.2 Tabletop scenarios						
ICVI	CI_Lower	CI_Upper	Kappa	SCVI_Avg	SCVI_Prop	ICC
0.96	0.44	0.99	−0.33	0.85	0.66	−0.07
1.3 Preparedness Assessment tool						
ICVI	CI_Lower	CI_Upper	Kappa	SCVI_Avg	SCVI_Prop	ICC
0.85	0.35	0.95	−0.32	0.85	0.66	−0.07

2. Sentiments score analysis					
2.1. ANOVA results for the validators sentiment types					
Term	Degrees of freedom	Sum squares	Mean squares	F value	*p* value
Validators	6	0.01	0.01	0.01	0.99
Sentiment_Type	3	63.898	21.299	288.024	0.000***
Item	57	0	0	0	1
Residuals	1,422	105.16	0.07	NA	NA

***0.001;
**0.01;
*0.05.

The ANOVA test results in Table 2 revealed a statistically significant effect of sentiment type on scores (F = 288, $p < 0.001$), indicating the robust influence of sentiment categories on validator scoring patterns. In contrast, neither the validator nor the item significantly affected the scores, as evidenced by F-values close to zero and p-values of 1, suggesting consistent scoring across validators and items.

Analysis of the Delphi Survey Responses

Descriptive and consensus analysis results

The responses across the survey items indicated a high degree of agreement, with mean scores predominantly between 4.5 and 4.97, indicating a strong inclination toward positive endorsement of the presented statements. The median remained at a maximum value of 5 for most questions, suggesting a commonality in expert opinions toward the upper end of the scale. In some cases, the IQR was narrow or zero, reflecting a tight concentration of responses around the median and suggesting limited variability in experts' judgments (Table 3). The percentage of agreement with the statements was high, reaching a 100% consensus among the experts in some cases. The lowest recorded agreement was observed among the majority (55%). The coefficient of variation ranged from 3.18% to 55.86%, illustrating the relative variance of the mean scores. Further, the average Kendall's W values ranged from 0.70 to 0.85 across all the themes, indicating a well-aligned expert consensus on the different components of the CBRN preparedness assessment tool, response flowchart, and scenarios (Table 3 and Appendix 3).

The consensus analysis indicated a strong shared perspective among experts regarding the fundamental principles included in

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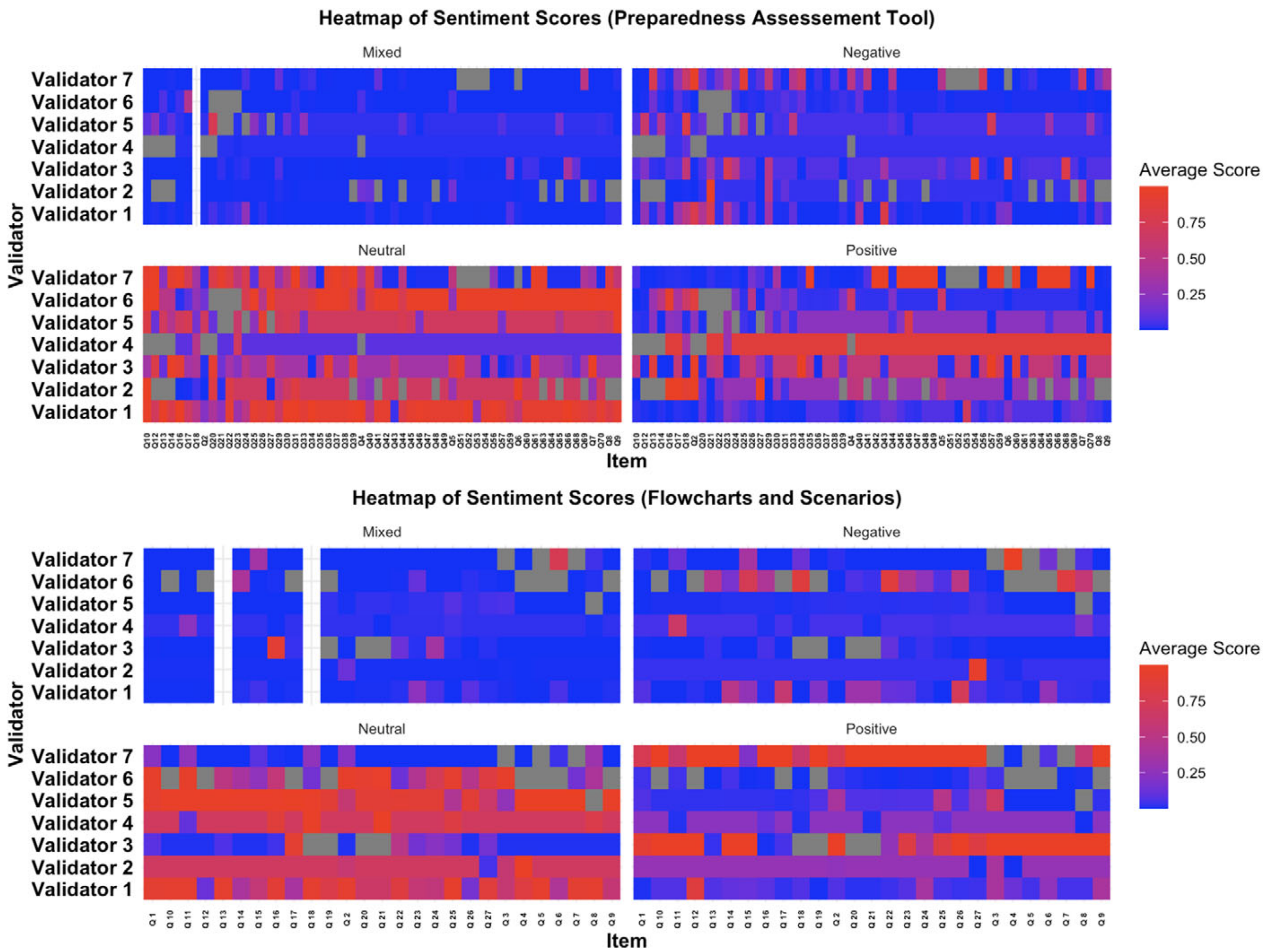

Figure 1. Validators' feedback sentiment repartition on the Delphi Tools' questions.

the tools. Appendix 3 provides the detailed results of the descriptive analysis.

Unsupervised machine-learning results

The clustering analysis utilizing t-SNE and k-means AI methodologies was employed to segregate experts' responses based on the countries they represented. Figures 2 and 3 and Appendix 4 demonstrate the 4 distinct clusters demarcated by particular demographic profiles and affiliations.

Cluster 1 included 7 experts with a mean age of 38.9 years and an average professional experience of 4 years, characterizing this ensemble as mid-career professionals predominantly from the MENA region. Cluster 2 comprised 4 experts, predominantly from Australasia, with a mean age of 31.5 years and a mean professional experience of 3.25 years. Cluster 3 included 14 experts with a mean age of 56.7 years and an extensive average experience of 23.7 years, comprising representatives from a few MENA countries and Canada, specifically Alberta, demonstrating a unified perspective on the indispensable components and preparedness required for the CBRN response, as suggested by this study. Cluster 4 constituted 15 experts with a mean age of 43.6 years and a mean professional experience of 11.5 years, indicating a group of well-established professionals. This cluster comprised experts from Europe, Tunisia, and MENA countries deeply influenced by European culture and sciences.

Discussion

The complicated nature of CBRN incidents necessitates a comprehensive approach to readiness assessment.[1] The MENA region is characterized by diverse challenges; therefore, the timely development of robust risk-assessment tools is critical.[17-18] These tools should integrate key elements to ensure accurate calibration and maintain a high level of preparedness in the health sectors' responses to CBRN threats. The present study identified a significant consensus across various dimensions among the Delphi panelists. The preceding qualitative phase contributed to identifying and achieving a solid consensus on crucial aspects, such as "medical protocols and logistics"; "decontamination capabilities"; "specialized human resources"; "public health"; "national practice, prevention, preparedness, policies, and inter-regional coordination"; "research and development"; "post-incident recovery and rehabilitation"; "interagency cooperation and coordination"; and "legal and ethical considerations."

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Table 3. Delphi consensus metrics results among the panelists

Tools	Theme	Number of questions	Mean	Median	IQR	Agreement %	SD	Coefficient of variation %	Average Kendall's W	Agreement classification
Preparedness assessment	Medical Protocols and Logistics	8	4.67	5	0.5	93.44	0.61	13.19	0.76	Strong agreement
	Infrastructure Readiness for CBRN Incidents in the MENA Region	15	4.71	5	0.35	93.67	0.57	12.28	0.76	Strong agreement
	Decontamination capabilities	28	4.40	4.79	0.98	84.29	0.87	21.16	0.77	Strong agreement
	Specialised Human Resources Capabilities	8	4.46	4.81	0.88	84.06	0.86	20.14	0.75	Strong agreement
	Public Health, National Practice, Prevention, Preparedness, Policies and inter-regional Coordination	58	4.52	4.86	0.86	89.74	0.73	17.11	0.73	Strong agreement
	Research and Development	3	4.75	5	0.42	100	0.44	9.22	0.74	Strong agreement
	Psychological Support	2	4.78	5	0	95	0.52	10.86	0.85	Strong agreement
	Post-Incident Recovery and Rehabilitation	3	4.78	5	0.08	98.33	0.45	9.37	0.75	Strong agreement
	Interagency Cooperation and Coordination	4	4.79	5	0.25	96.88	0.48	10.06	0.70	Strong agreement
	Legal and Ethical Considerations	3	4.69	5	0.08	91.67	0.62	13.13	0.70	Strong agreement
Response flowchart		12	4.47	5	1.12	85.72	0.75	16.89	0.72	Strong agreement
Table-top Case scenarios		4	4.54	5	1	90.63	0.67	14.76	0.71	Strong agreement

First, effective CBRN responses are based on robust, unified medical protocols and logistics.[24] Efficient and unified protocols across the region ensure timely and effective medical responses, whereas logistics are crucial for delivering the necessary supplies and resources and identifying local, national, and transnational limitations, such as mutual aid treaties and agreements to bolster logistics, enabling the continuous refinement of the medical response protocol. The absence of well-defined protocols in past health crises, such as the Ebola outbreak, has resulted in inefficiencies, exacerbating many health-care systems.[25,26] Second, ensuring sufficient decontamination capabilities is crucial in the CBRN management process.[27,28] The ability to decontaminate affected individuals promptly and effectively can significantly reduce the spread of hazardous substances and limit their clinical impact. The Novichok incident in 2017 in the UK demonstrated the importance of decontamination, where rapid responses helped limit the spread of contamination.[18,29] Third, ensuring well-trained and specialized human resources remains crucial. The complexity of CBRN incidents necessitates expertise beyond regular medical training.[30] The severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) pandemic highlighted the need for specialized skills in handling infectious diseases, demonstrating the importance of this element.[31] Fourth, coordinated public health approaches, national practices, prevention strategies, preparation plans, and policies are essential. Diseases and contaminants often transcend national boundaries; therefore, integrating interregional coordination empowers comprehensive preparedness by elevating vigilance and cooperation levels to develop logistics and training capabilities. An example of this is the recent e-NOTICE project in Europe, wherein multiple countries collaborated to establish unified training and discuss a unique response plan across their region.[32] The successful containment of the Middle East Respiratory Syndrome coronavirus in the MENA region is a testament to effective public health coordination.[33] Fifth, continuous research and development ensures that response strategies are based on the latest scientific knowledge and technological advancements. The rapid developments in SARS-CoV-2 vaccines constitutes a prime example of research altering the course of a health crisis. Furthermore, research assists in improving training plans through day-to-day update strategies and techniques.[3,10] Sixth, effective recovery and rehabilitation strategies are crucial for restoring normalcy and preventing long-term consequences, as the aftermath of a CBRN incident can be as challenging as the incident itself. The long-term health and environmental impacts of the Chernobyl disaster illustrate the need for robust post-incident strategies.[34] Seventh, the synergy between different agencies, including health, emergency services, and law enforcement, is crucial for effectively managing safety challenges concerning CBRN incidents. Finally, legal frameworks guide responses to CBRN incidents, whereas ethical considerations ensure that the responses are humane and just. The Ebola and SARS-CoV-2 outbreaks have raised numerous ethical issues, from quarantine to treatment prioritization.[35]

Furthermore, validation of the response flowcharts (Appendix 5) by an international panel of multidisciplinary experts from various geographical areas confirmed their applicability and robustness in diverse settings and attests to the flowcharts' comprehensive nature and capacity to be universally implemented. These flowcharts meticulously address the cultural challenges inherent to the MENA region by incorporating strategies that

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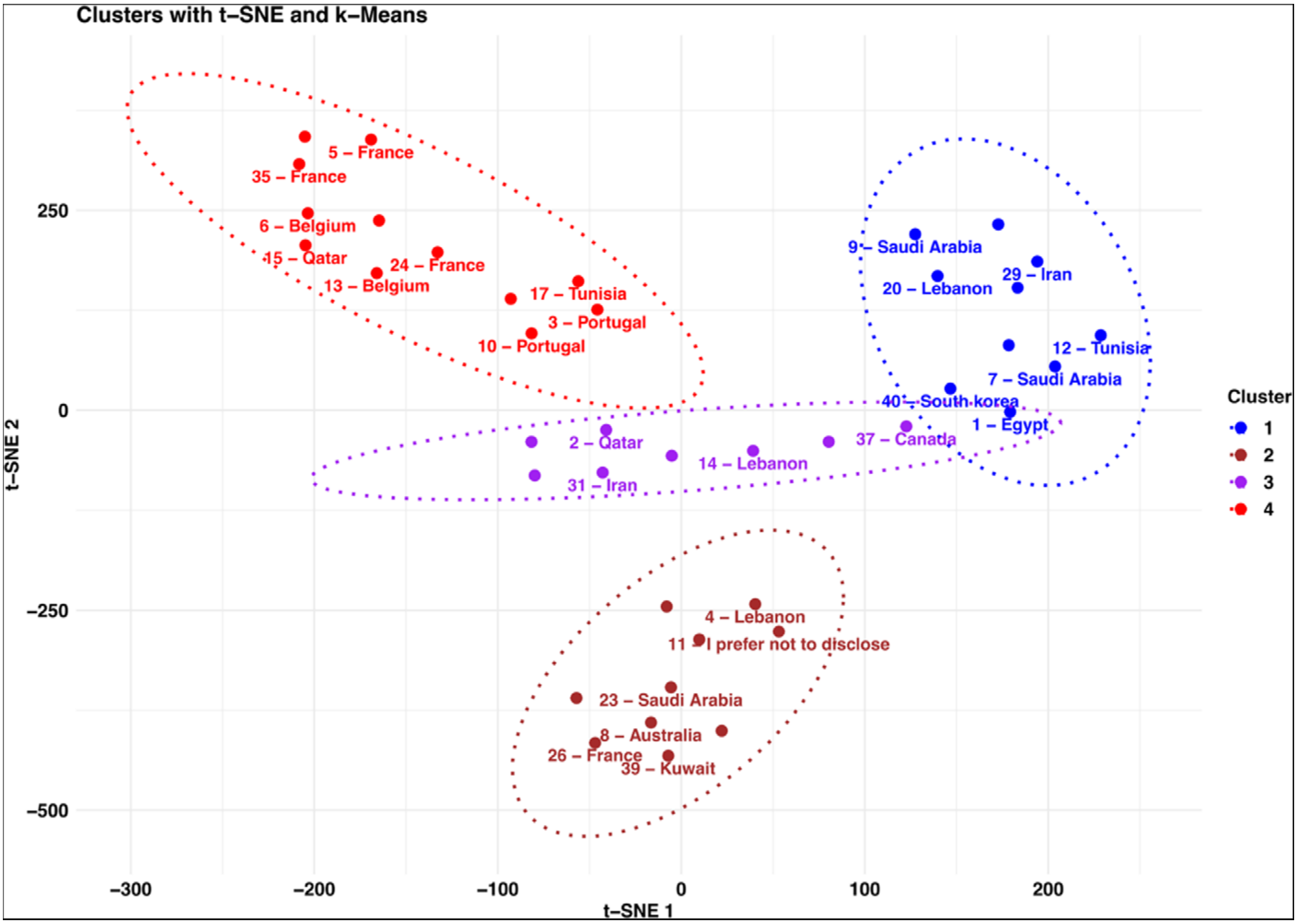

Figure 2. Unsupervised machine-learning clustering analysis according to the experts' countries.

account for women who are veiled, including those wearing a hijab or Christian nuns, thereby ensuring effective response measures that are sensitive to cultural practices. These flowcharts also consider the complexities posed by multilingual contexts and accents, which are critical for clear communication during CBRN incidents. Furthermore, these flowcharts provide special considerations for scenarios involving high-profile individuals or presidential personnel victims in CBRN incidents and recognize the unique risks that their presence might pose to the safety of others at the scene, attracting secondary attacks. These flowcharts emphasize the importance of defining "very important personality" based on political profile rather than wealth, as the former may be more relevant in CBRN incidents. Ultimately, the response flowcharts outline measures ensuring all parties are treated equitably, without compromise.

Moreover, tabletop scenarios (Appendix 6) simulating various CBRN emergencies have been developed to enhance the preparedness of pre-hospital and in-hospital staff. These scenarios are grounded in real-life incidents and aim to bridge theoretical knowledge with practical applications and test the multidisciplinary response capabilities of medical personnel. In a previous trial involving health-care professionals, exercises were refined based on feedback to ensure realism and relevance.[36] Tabletop exercises are crucial for improving health-care responses to CBRN threats, strengthening health-care personnel resilience and equipping them with essential skills and knowledge.[37,38]

Lastly, machine learning markedly refined the analytical approach of stratifying outcomes according to the geographical area of experts' consensus on CBRN preparedness and response strategies. It differentiated the perspectives of those from the MENA region (Cluster 1), experienced experts from Canada, and select MENA countries (Cluster 3), thereby enhancing the specificity and efficacy of the response protocols. Similarly, contributions from established professionals in Europe and Tunisia (Cluster 4) guided the customization of protocols to reflect European cultural and scientific influences.

In the present study, the deployment of machine-learning techniques helped deepen the understanding of the subject matter through a rich analysis of expert opinions, steering the creation of more refined and contextually relevant CBRN strategies. This highlights a pivotal moment in leveraging distinct areas of expertise and crafting flexible and comprehensive frameworks to navigate the complex global landscape of CBRN threats.

Limitations

This study has some limitations. More than 100 invitations were extended to experts across multiple countries, particularly in the

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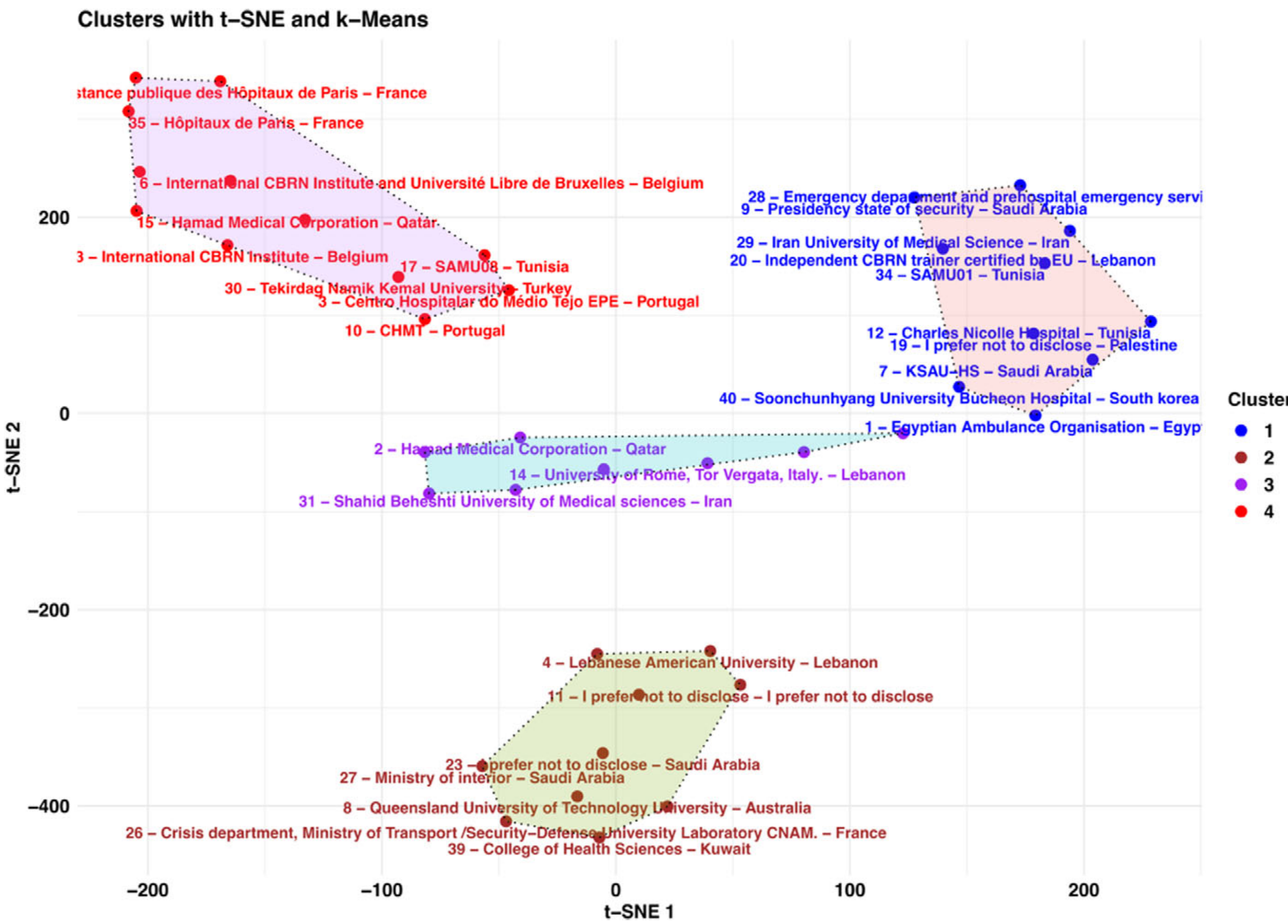

Figure 3. Delphi panelists' response clusters according to their institution (the overlaps are removed).

MENA region. However, the response rates of experts in Western countries were markedly higher than those of experts in the MENA region. This discrepancy highlights a divergent valuation of research engagement in the MENA region and a notable caution among its experts toward participating in research initiated outside their immediate organizational or national environment. Therefore, the underrepresentation of MENA experts in this study's findings may reflect a broader issue of regional engagement in research, indicating the need for strategies that foster a more inclusive and cooperative international research environment. Developing strategies to boost participation from underrepresented areas is essential for future studies. This includes forming partnerships in the MENA region to build trust, undertaking outreach to address concerns about international research, clearly explaining the study's benefits and privacy safeguards, and using culturally aware communication and local networks to raise awareness. Additionally, demonstrating the potential benefits through examples of impactful research, such as the present study, can encourage participation.

Conclusions

This study contributes significantly to CBRN preparedness and response in the MENA region by integrating AI methods to validate the proposed measures and explore the consensus among international experts. The innovative use of AI facilitated the fruitful analysis of experts' opinions, pinpointing areas of substantial agreement that form the nucleus of the proposed risk assessment tool. These consensus-driven components were identified as critical for effective preparedness and management of CBRN incidents, necessitating rigorous testing before their practical application.

Furthermore, this study developed and validated response flowcharts and scenario-based exercises. These tools should be employed to develop a comprehensive and immersive training program, which can be potentially augmented by reality-enhancing technologies, such as virtual reality. This approach can ensure that the response mechanisms are both practical and adaptable to the dynamic nature of CBRN threats.

The innovative approach of this study in deploying AI computing techniques with expert consensus analysis and practical validation exercises not only enhances the results but also identifies future opportunities for such approaches. Building upon this study's contributions to CBRN preparedness, future research should explore enhancing AI methodologies for broader input from experts and refining risk assessment tools. Integration of augmented and mixed reality into training courses offers a potential for more real-world simulations. Further, collaborative international studies involving a broader range of experts can enhance the generalizability and robustness of the findings, ensuring that the developed strategies are globally applicable and effective in various disaster scenarios.

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Data availability statement. The data is available with the first author and can be provided upon reasonable request.

The Delphi survey questions can be accessed through this link: https://survey.phonic.ai/6575c9fda6c6b22db1d52e44?preview=true.

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