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Simulation technology use in disaster medicine education and training: a scoping review

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Background: Disaster medicine (DM) education has increasingly turned to simulation technologies to address the limitations of traditional training methods. Tools such as virtual reality, mobile applications, and e-learning platforms offer immersive and repeatable learning environments. However, the rapid growth of these tools has outpaced efforts to synthesize how they are being applied, what learning goals they target, and how outcomes are reported.

Objective: This scoping review aimed to map the current evidence on how simulation technologies are used in DM education and training, with a focus on the educational objectives addressed and the types of tools and metrics reported.

Methods: Following the PRISMA-ScR guidelines, a comprehensive search of four databases (PubMed, Scopus, Web of Science, and IEEE Xplore) identified original studies published between 2000 and 2024. Thirty-two studies met the inclusion criteria. Data were charted on the type of technology, training topic, learning group, and evaluation methods.

Results: Mass casualty triage was the most frequently addressed topic. Virtual reality, mobile application, and serious games were the most common modalities. Most studies reported improvements in knowledge, triage accuracy, or learner confidence. However, evaluation strategies varied widely, with most relying on short-term knowledge tests or self-reported confidence. Few studies addressed the realism of the training environments or the integration of digital tools into broader instructions frameworks.

Conclusion: Technology-enhanced DM education shows promise, particularly for immersive triage training. However, inconsistent evaluation practices and limited curricular integration highlight the need for more rigorous, outcome-aligned research to support effective use of simulation technology in this field.

KEYWORDS
disaster medicine education, simulation technology, virtual reality, mass casualty incidents, mass casualty triage

1 Introduction

As the frequency and complexity of disasters continue to increase worldwide (1), the need for competency-based training in disaster response has become more urgent. Educational programs have shown promise in improving disaster readiness (2). However, traditional methods such as lectures and live drills often face logistical and financial constraints, making it difficult to expose learners to realistic scenarios in a safe way (3). This has contributed to growing interest in innovation in educational delivery, particularly through the use of emerging technologies (4).

In recent years, simulation technologies have increasingly been integrated into Disaster Medicine (DM) training to overcome the limitations of traditional methods and expand access to immersive learning experiences. Digital tools such as virtual reality (VR), mobile apps, e-learning platforms, and mixed-reality simulations are increasingly adopted to enhance not only knowledge acquisition, but also practical skills and decision-making under pressure. These technologies have also been explored in multiple domains of disaster management including preparedness, training, and real-time simulation. They offer repeatable exposure to complex scenarios, ease the logistical burden of live drills, provide real-time feedback on learner performance, are generally well received by users in terms of engagement and perceived preparedness (5, 6). Reviews suggest these applications may improve learner immersion, self-efficacy, and preparedness in disaster training.

While the adoption of these tools has been accelerated by broader trends in digital health and simulation, questions remain about how effectively they are being designed, integrated, and aligned with specific learning objectives (7). Furthermore, the growing operational use of simulation technologies in disaster response highlights the need to ensure that training environments mirror the complexity of the real-world systems they intend to prepare learners for.

Despite the growing application of new technologies in DM education, the current body of literature remains fragmented and uneven. Much of the existing research appears to focus on specific tools, with relatively few studies offering broader or comparative perspectives (5).

In addition, there appears to be limited synthesis on how various technologies are applied hacross different educational objectives and on the tools used to evaluate these outcomes. Questions remain about the consistency and rigor of outcome measurement across different modalities and training contexts.

Building on these observations and given the increasing reliance on digital tools in DM training, there is a clear need to map how these simulation technologies are currently being used and evaluated. Thus, we performed a scoping review to understand not only which technologies are being adopted, but also what educational goals they aim to achieve and how their effectiveness is being measured.

2 Methods

2.1 Approach

A scoping review methodology was chosen and conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, exclusively with its extension for scoping reviews (PRISMA-ScR) (8), as it allows for the comprehensive mapping of the broad, interdisciplinary body of research on disaster medicine education and training that integrates new technologies for educational purposes. Supplementary Table 1 presents the corresponding PRISMA-ScR Checklist.

Through this approach, we aim to address the following research questions:

- RQ1: What is the current evidence of the utilization of simulation technologies in disaster medicine education and training?
- RQ2: What tools and metrics were used to measure effectiveness of these trainings?

2.2 Eligibility criteria

To ensure a comprehensive review, we included all original studies that reported on technological innovations in DM education. Eligible study designs encompassed experimental, quasi-experimental, mixed-methods, and feasibility studies. The training programs targeted healthcare professionals including physicians, nurses, paramedics, and students or residents, and aimed to develop disaster-related knowledge and skills. Interventions had to incorporate technology-based educational methods, including but not limited to mixed reality, simulation platforms, mobile applications, e-learning tools, gamified systems, smart devices, sensor-based tools, or any communication and information technologies (ICTs). Only peer-reviewed articles published in English from the year 2000 onward were included, with no geographical restrictions.

2.3 Information sources and search strategy

We conducted a comprehensive literature search across four electronic databases: PubMed, Scopus, Web of Science, and IEEE Xplore. The search was conducted in July 2024. It covered publications from January 1, 2000, to the date of the final search.

The search strategy combined terms related to DM and emergency preparedness (e.g., disaster, mass casualty, emergency medicine) with terms related to education and training (e.g., education, training, simulation) and simulation technology (e.g., virtual reality, mobile app, e-learning, ICT, smart, gamification). Boolean operators (AND, OR) and truncation were applied to maximize sensitivity. Supplementary Table 2 presents the implemented search string.

2.4 Selection process and data collection

Following the above eligibility criteria, titles and abstracts were first scanned independently by two reviewers (JGU, MAK), with the support of the software CADIMA (9), to select articles for in-depth analysis if both reviewers agreed upon. This web-based software platform streamlines the screening and data extraction process. After the initial screening process, reviewers assessed the full-text eligibility for inclusion. During the full-text screening phase, studies were selected only if there was an agreement among the reviewers, and a third researcher (BA) acted as arbitrator when there was no consensus. Subsequently, a comprehensive data extraction sheets was created to extract relevant information for thematic analysis. The primary author (JGU) extracted information about each included study, including the first author, publication year, country, study design, the number and type of participants, and details about the intervention. This information encompassed the type of simulation technology used, the comparator, and the training content. Additionally, results regarding the impact of the training and the methods employed to measure this impact, such as metrics and tools, were also collected.

2.5 Data synthesis and analysis

Data from the included studies was collated and tabulated to provide a comprehensive overview of the use of simulation technology in DM education and training. A semi-quantitative analysis using descriptive statistics was conducted to summarize the key characteristics of the studies. After identifying the overall trends, a qualitative synthesis was performed to gain deeper insights into the main topic, as well as the most commonly used tools and metrics.

3 Results

3.1 Search

The search retrieved a total of 1,917 articles from the four databases. After removal of duplicated (n = 598), the titles and abstracts of 1,319 records were screened for eligibility. Of these, 161 articles were selected for full-text review by the authors, resulting in 32 studies that finally met the established inclusion and exclusion criteria to be included in this scoping review. This literature search process is presented in the PRISMA flow-chart (Figure 1).

3.2 Study characteristics

Publications date from 2000 to 2024. 16 records were conducted in North America, particularly the United States, while the other half of studies are from East Asia and Europe. Over half of the studies adopted quasi-experimental designs (n = 17) (10–26), others utilized randomized controlled trial design (n = 12) (27–37), feasibility or pilot designs (n = 2) (38, 39) and qualitative methods (n = 1) (40). A comprehensive summary of the extracted data is provided in Table 1.

Eight studies targeted an audience composed in first place by Emergency Medical Services (EMS) professionals. Following, five studies (16, 21, 22, 33, 41) delivered to undergraduate medical students, four studies to professional nurses (13, 25, 26, 35), three (11, 14, 20) to undergraduate paramedicine students, and other three studies to undergraduate nursing students. One study (40) on mental health specialists, another on professional paramedics, and one last study (15) on civil protection operators. The number of participants per study ranges from 4 to 120. The total number of participants was 1.464 among all studies, professional nurses being the most frequents (n = 340), followed by EMS personnel (n = 300), and medical students (n = 263).

Regarding the content, fifteen training courses aimed to the carrying out of execution of patient triage during MCIs, followed by four studies (13, 18, 26, 29) on decontamination in Chemical, Biological, Radiological, Nuclear, and high yield Explosives (CBRNE) disaster scenarios, and another four (24, 30, 37, 41) on general concepts of disaster management. Two studies (16, 21) on flood and earthquake evacuations, two studies on outbreak/pandemic preparedness (25, 38), and two other studies (35, 40) on mental health support in disasters. Lastly, the studies on hospital disaster preparedness (17), civil protection rescuing procedures (42), and in EMS executive management (20), were the least represented.

Technology-based trainings were primarily delivered using various forms of virtual reality (VR) simulation; from thirteen articles using desktop-based simulation (14, 18, 20, 25, 27, 28, 30, 33, 34, 36, 37, 41, 43), to five studies (11, 15, 16, 26, 38) utilizing fully immersive simulation methods. Successively, e-learning platforms were reported in four articles (10, 17, 24, 35), followed by high-fidelity mannequins (12, 22, 23), augmented reality (31, 39), mobile-based technology (21, 40), 360° immersive simulation (13), video-based trainings (29), and text-based mobile messaging (32). The relationship between technology used and topics taught can be appreciated in Figure 2.

Examples of desktop-based simulations range from simple disaster footage projected on screen walls and trainees' individual screen-based multi-patient scenario (30), to the VR system CAVE, which is a full-immersion virtual environment enclosed by walls, floor, and ceiling, creating a realistic replica of a disaster using sophisticated three-dimensional computer-based imaging (27), the serious game *"60 Seconds to Survival"* (44), a tabletop virtual system (14), the online virtual simulation *"Second Life"* (45), simulation model of a regional EMS system that replicates the course of action after a 911 call (20), and the XVR training software (33). In these, extended reality (XR) accessories such as joysticks were utilized, and victims were simulated by avatars, sometimes replicating standardized patients. Head-mounted displays and tracking sensors were used by fully immersive simulations, exposing participants to the sensorial challenges of close-to-real disaster scenarios, to train and evaluate their behavior during exercises.

Notably, in all but one of the included studies, participants actively engaged with the technology themselves. In contrast, McCoy et al. (39) assessed the feasibility of a disaster course delivered via tele-simulation. In their study, an instructor used smart glasses to stream a live, interactive MCI scenario while acting as a paramedic evaluating victims and verbalizing key clinical information to remote learners.

Twenty-one studies had a least two training groups, four of which compared a type of virtual reality simulation (fully immersive, 360° immersive, augmented reality, and desktop-based) with traditional lecture sessions (11, 29, 35, 41), and other 11 studies with conventional live training methods (13, 16, 24–27, 33, 34, 36, 43, 44). The remaining five studies implemented a variety of other digital technologies; for instance, e-learning platform were used in two studies comparting with text-based traditional education and live simulation (24, 35). One study used

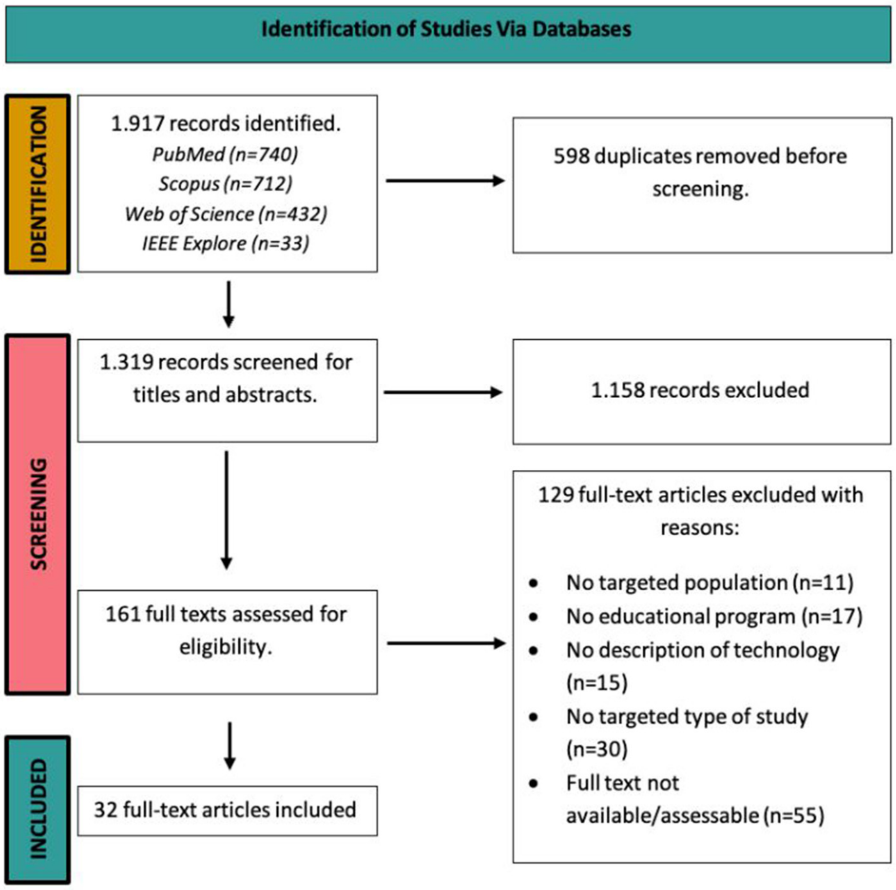

FIGURE 1
PRISMA flow diagram.

video-based footage to compare CBNRE training performance against traditional lecture (29). Another study compared a text-based messaging mobile application with traditional voice over two-way radio during disaster simulation (32). One study used a mobile-based simulation app comparing with paper-based hazard maps to teach flood evacuation steps (21). Lastly, one study didn't introduce a comparator, rather confronted the performance of both groups on CBNRE disaster scenarios (18).

The remaining 11 articles had only one group that undertook either one or more tech interventions (10, 12, 14, 15, 17, 20, 22, 23, 38–40). Among these, two were feasibility studies of fully immersive and augmented reality (38, 39), and one compared two triage systems using the same desktop-based VR simulation method (SALT vs. SMART) (14).

Finally, it is worth noticing that the included articles revealed a research trend over the last 20 year, accentuated on the study of mass casualty triage, which can be appreciated in Figure 3.

3.3 Mass casualty triage

The majority of the studies taught triage, either alone (10–12, 14, 22, 23, 27, 31–34, 36, 39, 43, 44) or in combination with other related content (13, 17, 18, 26, 29, 30, 41). Assessed as triage accuracy and time to triage, alongside with knowledge acquired, treatment/intervention accuracy, and performance correctness, these studies investigated the use of technology-enhanced educational strategies to train healthcare professionals and students in triage protocols under disaster conditions. Table 2 provides an insightful overview of this thematic cluster.

Desktop-based virtual reality was the most commonly used single tech to teach triage for MCIs (14, 18, 27, 30, 33, 34, 36, 41, 43, 44). These platforms immersed learners in virtual MCI scenarios where they were required to perform patient assessments, prioritize interventions, and allocate resources. Notably, some VR environments were found to offer better data capture and time-stamped data on triage actions, enhancing the granularity of performance assessment (14), although challenges such as user navigation difficulties (30) and low scenario novelty (44) were also reported.

Fully immersive VR and 360° VR simulations provided a more sensorial engaging experience, used to replicate high-pressure disaster environments. Studies using these methods (11, 13, 38) reported strong user engagement and perceived training value. However, technical barriers such as complex controls, hardware discomfort, and high costs were

TABLE 1 Included studies.

References and country	Study design	Sample	Aim(s)	SIM scenario	SIM tech	Comparator	Measure(s)
Andreatta et al. (27) United States	Randomized controlled trial	15 Medical residents	Compare fully immersive VR disaster drills vs. live standardized patient drills for START triage training	Building explosion	Desktop-Based Virtual Reality Simulation	standardized patient (SP)	Ability to ensure safety of scene, triage assessment, triage accuracy, and knowledge retention
Báez et al. (10) United States	Quasi-experimental study	55 EMS personnel	Train EMS providers in mass casualty triage using an asynchronous e-learning course	Mass casualty incident with five standardized scenarios based on the START system	E-Learning and Web-Based Training	N/A	Triage ability, short-term skill retention
Bednar et al. (38) Czech Republic	Observational study—pilot study	10 EMS personnel and students	Train paramedics and students in MCI response and infectious disease management using VR	Car accident scenario, and highly contagious disease scenario	Fully Immersive Virtual Reality Simulation	N/A	Procedural correctness, user experience
Behmadi et al. (11) United States	Quasi experimental study	44 Paramedicine students	Compare VR-based vs. lecture-based training for teaching START triage to paramedicine students	No disaster setting, only triage lecture	Fully Immersive Virtual Reality Simulation	Traditional lecture	Teaching efficiency, student perception
Bentley et al. (12) United States	Quasi-experimental study	4 EMS personnel, and an audience of 168 mixed healthcare providers	Teach MCI triage, resource management, and hospital bed allocation using high-fidelity simulation	Gas line explosion	High-Fidelity Mannequins and Live-Action Simulation	N/A	Triage accuracy, teamwork, self-reported confidence
Chang et al. (13) Taiwan	Quasi-experimental study	67 Nurses	Evaluate nurses' preparedness and self-efficacy in chemical disaster response	Three victims of a factory explosion disaster	360° Immersive VR Simulation	Tabletop drill	Chemical disaster preparedness, self-efficacy
Choi et al. (40) South Korea	Qualitative study—focus group	30 Mental health specialists	Analyze mental health specialists' experiences providing Psychological First Aid (PFA) using a mobile simulation app	Flood, fire, or leakage of hazardous chemicals	Mobile-Based Training and Simulation Apps	N/A	Experience using PFA mobile app
Cicero et al. (43) United States	Nested cohort within a randomized controlled trial	26 EMS personnel and students	Evaluate whether screen-based triage training translates to improved accuracy in immersive simulations	Mass shooting at a high school, a multiple family house fire, and a shopping mall struck by a tornado	Desktop-Based Virtual Reality Simulation	Live simulation	Correlation between screen-based and immersive triage accuracy
Cicero et al. (28) United States	Randomized controlled trial	62 EMS personnel and students	Train EMS providers and students in START/JumpSTART triage and life-saving maneuvers using a VR serious game	School shooting, multiple-family house fire, and tornado	Desktop-Based Virtual Reality Simulation	Live simulation	Triage accuracy
Cone et al. (14) United States	Quasi-experimental study	22 Paramedicine students	Assess paramedic students' triage accuracy and speed using two triage systems in a VR highway bus crash scenario	Highway bus crash	Desktop-Based Virtual Reality Simulation	Triage systems	Triage accuracy, and triage speed
Curtis et al. (29) United States	Randomized controlled trial	26 Medical residents	Compare video-based vs. traditional disaster medicine education of a chemical disaster	CBRNE	Video-Based Training	Traditional lecture	Knowledge, confidence, practical skill implementation
De Lorenzis et al. (15) Italy	Case report	22 Civil protection personnel	Train civil protection operators in high-capacity pumping (HCP) procedures using immersive VR	Hydrogeological disaster scenario	Fully Immersive Virtual Reality Simulation	N/A	Knowledge gained, user experience

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TABLE 1 (Continued)

References and country	Study design	Sample	Aim(s)	SIM scenario	SIM tech	Comparator	Measure(s)
Farra et al. (30) United States	Randomized controlled trial	32 Nursing students	Evaluate VR disaster simulation effectiveness for disaster knowledge acquisition and retention in nursing students	MCI Triage scenario, and a decontamination exercise	Desktop-Based Virtual Reality Simulation	Web-based learning modules only	Knowledge acquisition, knowledge retention
Feng et al. (16) New Zealand	Quasi-experimental study	99 Medical students	Teach earthquake evacuation best practices and safety behaviors using an immersive VR headset	Earthquake	Fully Immersive Virtual Reality Simulation	Paper-based lecture, and VR without repetition	Safety knowledge, self-efficacy, training experience
Follmann et al. (31) Germany	Randomized controlled trial	31 Paramedics.	Test Smart Glasses' feasibility and effectiveness for paramedics in triage decision-making	An explosion in a row of residential buildings	Augmented Reality and Smart Glasses	No access to tech, and tele-assistance	Triage accuracy, speed, and user experience
Franc-Law et al. (17) Canada	Quasi-experimental study	33 Mixed healthcare providers	Evaluate a hospital emergency department disaster plan using an online virtual-life exercise	Multiple vehicle collision, followed by a domestic disturbance	E-Learning and Web-Based Training	N/A	Patient flow, participant satisfaction
Goldberg et al. (32) United States	Randomized controlled trial	53 Medical residents	Compare disaster communication accuracy using text-based messaging vs. voice radio in an earthquake scenario.	Earthquake that paralyzed the electrical grid and telecommunication networks	Communication Technology	Voice transmitted over two-way radio (VOICE-TWR).	Communication accuracy, triage accuracy, workload, user experience
Heinrichs et al. (18) United States	Observational study	22 Mixed healthcare providers	Assess the usability of a Virtual Emergency Department (VED) for MCI training of physicians and nurses	CBRNE bomb blast	Desktop-Based Virtual Reality Simulation	N/A	Knowledge, user experience
Hu et al. (19) China	Quasi-experimental study	68 Medical students	Compare game-based learning vs. lectures for hospital disaster management training in medical students	MCI Triage scenario	Desktop-Based Virtual Reality Simulation	Traditional lecture	Knowledge gain, knowledge retention
Hubble et al. (20) United States	Quasi-experimental study	21 Paramedicine students	Evaluate EMS management skills for paramedicine students	Emergency and non-emergency scenario	Desktop-Based Virtual Reality Simulation	N/A	EMS response time, ambulance utilization, return on investment, return on asset, and net profit
Ingrassia et al. (33) Italy	Randomized controlled trial	56 Medical Students	Compare VR vs. live simulation for mass casualty triage training in medical students	Car accident	Desktop-Based Virtual Reality Simulation	Live simulation.	Triage accuracy
Knight et al. (34) United Kingdom	Randomized controlled trial	91 EMS Providers	Evaluate the effectiveness of a VR serious game in teaching major incident triage skills to EMS providers	Domestic outdoor gas explosion accident	Desktop-Based Virtual Reality Simulation	Paper-based training: Card-sort	Triage accuracy, step accuracy, and the time taken to triage all casualties
Ko and Choi (35) South Korea	Randomized controlled trial	93 Nurses	Train nurses in psychological support for disaster-affected patients through an e-learning program	Infectious disase disasters	E-Learning and Web-Based Training	Text-based education materials	Disaster mental health competence, problem-solving, self-leadership, motivation

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TABLE 1 (Continued)

References and country	Study design	Sample	Aim(s)	SIM scenario	SIM tech	Comparator	Measure(s)
Matsuno et al. (21) Japan	Quasi-experimental study	20 Medical students	Teach medical students flood evacuation planning using a smartphone-based VR serious game	Flood disaster	Mobile-Based Training and Simulation Apps	Hazard maps	Mapping skills, flood disaster awareness
McCoy et al. (39) United States	Observational study - feasibility report	32 EMS Providers	Assess feasibility of using Google Glass for MCI triage training through pre-recorded scenarios	Active shooter in an office building	Augmented Reality and Smart Glasses	N/A	Feasibility of Google Glass training, triage accuracy, user perception
Shubeck et al. (36) China	Randomized controlled trial.	20 EMS personnel and firefighters	Compare virtual training vs. live-action training for EMS providers and firefighters in MCI triage	Earthquake	Desktop-Based Virtual Reality Simulation	Live-action training simulation	Knowledge, triage accuracy, attitudes toward training
Tao (37) China	A two-arm randomized controlled trial	92 Nursing students	Train nursing students in prehospital emergency care (assessment, triage, treatment) using VR simulation	The simulation includes a noisy, bloody disaster environment (video on screen wall), and multiple injured patients (computer screen)	Desktop-Based Virtual Reality Simulation	In-class discussions	Operational skills, theoretical knowledge, teamwork, student perception
Vincent et al. (22) United States	Quasi-experimental study	28 Mixed healthcare providers	Test high-fidelity manikins' effectiveness in MCI triage training for mixed healthcare providers	Bomb blast, a bus accident, a building collapse, and another large explosion	High-Fidelity Mannequins and Live-Action Simulation	N/A	Triage accuracy, learner satisfaction, self-efficacy
Vincent et al. (23) United States	Quasi-experimental study	20 Medical students	Assess triage speed, accuracy, and self-efficacy of medical students using high-fidelity manikins	Bomb explosion	High-Fidelity Mannequins and Live-Action Simulation	N/A	Triage accuracy, speed, and self-efficacy
Wiese et al. (24) United States	Quasi-experimental study	90 Nursing students	Compare introductory disaster knowledge retention between live and virtual simulations for nursing students	Tornado	E-Learning and Web-Based Training	Live simulation	Knowledge gained, self-assessment
Zhang et al. (25) China	Quasi-experimental study	120 Nurses.	Improve emergency nurses' public health emergency response skills through VR pandemic simulations	Infectious respiratory disease epidemic	Desktop-Based Virtual Reality Simulation	Conventional training: knowledge training and emergency drill	Emergency care capability, theoretical knowledge, disaster preparedness
Zhao and Li (26) China	Quasi-experimental study	60 Nurses	Train nurses in nuclear radiation emergency response, including PPE use, dosimetry, triage, and decontamination, using VR	Nuclear radiation emergency	Fully Immersive Virtual Reality Simulation	Conventional training: knowledge training and emergency drill	Operational skills, theoretical knowledge, confidence, satisfaction, teamwork

CBRNE, Chemical, Biological, Radiological, Nuclear, and Explosive; EMS, Emergency Medical Services; HCP, High-Capacity Pumping; MCI, Mass Casualty Incident; PFA, Psychological First Aid; PPE, Personal Protective Equipment; SIM, Simulation; SP, Standardized Patient; START, Simple Triage and Rapid Treatment; VOICE-TWR, Voice over Two-Way Radios; VED, Virtual Emergency Department; VR, Virtual Reality.

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	Desktop-Based Virtual Reality (VR) Simulation	Fully Immersive Virtual Reality (VR) Simulation	E-Learning & Web-Based Training	High-Fidelity Mannequins & Live-Action Simulation	Augmented Reality & Smart Glasses	Mobile-Based Training & Simulation Apps	360° Immersive VR Simulation	Video-Based Training	Text-based mobile messaging
MCI Triage	7	1	1	3	2	0	0	0	1
General DM Knowledge	3	0	1	0	0	0	0	0	0
CBRNE	1	1	0	0	0	0	1	1	0
Executive EMS	1	0	0	0	0	0	0	0	0
Outbreaks/Pandemic Preparedness	1	1	0	0	0	0	0	0	0
Civil Protection training	0	1	0	0	0	0	0	0	0
Evacuation	0	1	0	0	0	1	0	0	0
Hospital disaster management	0	0	1	0	0	0	0	0	0
Mental health	0	0	1	0	0	1	0	0	0

FIGURE 2
Common topics targeted by simulation technologies in included articles.

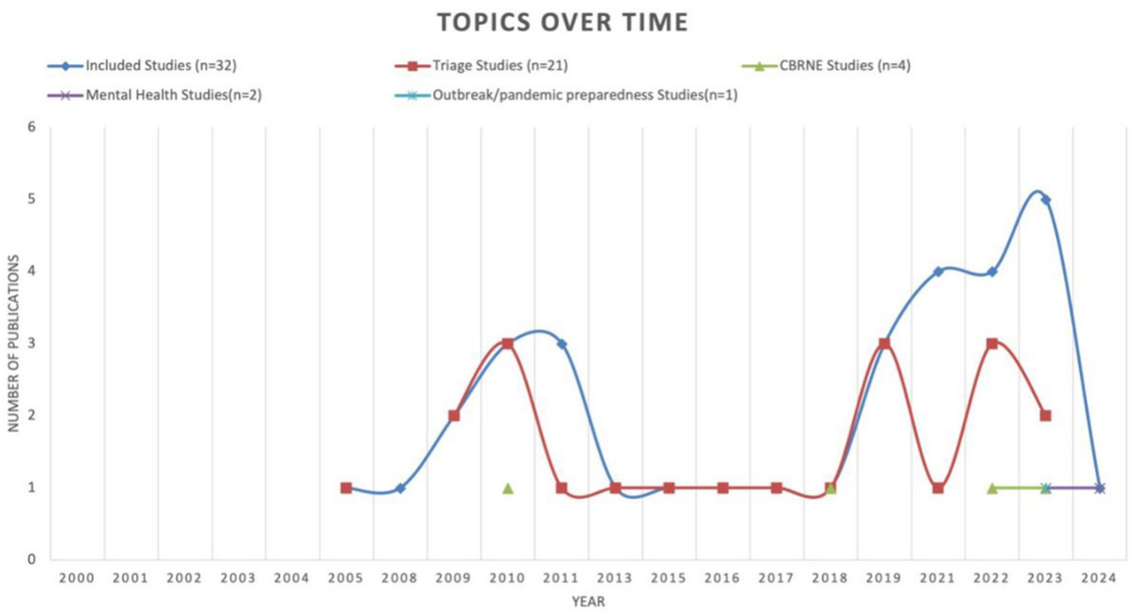

FIGURE 3
Most studied topics with integration of simulation technologies over time.

consistently mentioned. Augmented reality and smart-glasses-based interventions offered in two studies (31, 39) real-time overlays of clinical information or tele-simulation perspectives. These innovations were found to improve decision accuracy and broaden remote training possibilities, yet were limited by battery life, technical compatibility with eyewear, and the need for stable connectivity infrastructure.

E-learning modules (10, 17) and video-based trainings (29) provided more accessible formats for large-scale deployment. These studies showed consistent post-intervention improvements in knowledge and practical application, with Báez et al. reporting skill retention at one-month follow-up (10). Curtis et al. found video-based learners performed better in personal protective equipment (PPE) use and decontamination tasks than those taught via lecture (29). However, these methods lacked the experiential dimension of immersive platforms.

High-fidelity mannequins and live-actions simulations, featured in three studies (12, 22, 23), continued to play a valuable role in the hands-on skills development. While learners reported increased confidence and improved teamwork skills, high-fidelity mannequins were occasionally limited in replicating physiological responses.

TABLE 2 Technology-based approaches to mass casualty triage trainings.

References and Country	Tech intervention	Measure(s)	Assessment instrument(s)	Result(s)	Follow-up	Challenges or limitations
Andreatta et al. (27) United States	Desktop-Based Virtual Reality Simulation	Triage score, triage accuracy, and knowledge retention	Pre-test, Triage rating scale, and 2-week post-test for knowledge retention	There were no significant differences in triage performance between the VR and SP groups	2-week post-test for knowledge retention	Not mentioned
Báez et al. (10) United States	E-Learning and Web-Based Training	Triage accuracy, short-term skill retention	Pre- and post-intervention tests were administered, each consisting of five standardized scenarios based on the START system	Triage knowledge improved post-training and was retained at 1-month follow-up	1-month follow-up	Not mentioned
Bednar et al. (38) Czech Republic	Fully Immersive Virtual Reality Simulation	Procedural correctness, including tirage assessment, and user experience	Observer notes and self-assessment questionnaire	95% of participants found VR helpful for disaster training	N/A	VR controls were complex and distracting for some users
Behmadi et al. (11) United States	Fully Immersive Virtual Reality Simulation	Triage knowledge, student perception	Student exam scores and 7-item self-assessment questionnaire	Virtual simulation-based education had slightly higher mean scores than lecture-based education, but the difference wasn't statistically significant	N/A	Not mentioned
Bentley et al. (12) United States	High-Fidelity Mannequins and Live-Action Simulation	Triage accuracy, teamwork, self-reported confidence	Audience checklist and post-exercise questionnaire	Enhanced teamwork, triage decision-making, and confidence in MCI triage	N/A	Limited simulation time (8 min for 12 patients) may not reflect real-life MCI triage
Chang et al. (13) Taiwan	360° Immersive VR Simulation	Primary and secondary triage	Pre/post self-assessment disaster preparedness inventory and self-efficacy scale	VR enabled less-experienced nurses to achieve expert-level disaster knowledge	N/A	Not mentioned
Cicero et al. (43) United States	Desktop-Based Virtual Reality Simulation	Triage accuracy, amount of time taken to triage each patient, the order in which patients were triaged	Pre/post-intervention live simulations	No significant correlation between screen-based and immersive triage accuracy	N/A	Not mentioned
Cicero et al. (28) United States	Desktop-Based Virtual Reality Simulation	Triage time, accuracy, and efficiency	Pre/post-intervention live simulations	Significant improvement in triage accuracy in the intervention group	N/A	Lack of novelty in repeated plays—patients behaved identically in each session
Cone et al. (14) United States	Desktop-Based Virtual Reality Simulation	Triage accuracy, and time to triage	Integrated feedback system capturing keystrokes, triage actions, and timing	VR triage system provided higher-quality data than manual disaster drills	N/A	VR simulation did not account for time needed to perform life-saving interventions
Curtis et al. (29) United States	Video-Based Training	Patient triage, decontamination, and personal protective equipment use	Pre/post-knowledge test, comfort survey, practical skills assessment	Video-trained group outperformed lecture-trained group in practical skills		Not mentioned
Farra et al. (30) United States	Desktop-Based Virtual Reality Simulation	Patient assessment, triage, and first aid intervention	Pre/post-tests knowledge assessment (20-question multiple-choice test)	VR-trained group retained disaster knowledge better than non-VR group	2-month follow-up knowledge assessment	VR environment was difficult to navigate and manipulate
Follmann et al. (31) Germany	Augmented Reality and Smart Glasses	Time to triage, triage accuracy, usability, user experience	Observers recorded triage duration and category selection, and post-training questionnaire	Smart Glasses improved triage quality, but increased time needed for assessment	N/A	Smart Glasses had short battery life and lacked compatibility with personal eyewear
Goldberg et al. (32) United States	Communication Technology	Communication accuracy, triage accuracy, workload, user experience	Tabletop task accuracy, NASA TLX for workload, Systems Usability Scale (SUS)	Text-based disaster communication was more accurate and preferred over voice radio	N/A	Connectivity and battery life issues with wireless mesh network devices

(Continued)

TABLE 2 (Continued)

References and Country	Tech intervention	Measure(s)	Assessment instrument(s)	Result(s)	Follow-up	Challenges or limitations
Heinrichs et al. (18) United States	Desktop-Based Virtual Reality Simulation	Triage knowledge and accuracy, user experience	Pre/post-test quiz, exit survey, debriefing, and focus group discussion	Virtual ED was described as realistic, immersive, and effective for training	N/A	Users found VR environment difficult to navigate; avatar controls were challenging
Hu et al. (19) China	Desktop-Based Virtual Reality Simulation	Triage knowledge, knowledge retention	20-question pre/post-test	Game-based training improved disaster knowledge and retention	6-week follow-up knowledge test	Not mentioned
Ingrassia et al. (33) Italy	Desktop-Based Virtual Reality Simulation	Triage accuracy	Automatic VR recording for triage accuracy, researcher notes from live simulation	VR and live simulation were equally effective for triage training	N/A	Not mentioned
Knight et al. (34) United Kingdom	Desktop-Based Virtual Reality Simulation	Triage performance	Video recordings reviewed for triage accuracy	VR-trained students performed triage significantly more accurately	N/A	Not mentioned
McCoy et al. (39) United States	Augmented Reality and Smart Glasses	Feasibility, time to triage and accuracy, and user perception	Process evaluation, survey, and real-time participant triage accuracy data	Google Glass tele-simulation enhanced MCI triage training beyond lectures.	N/A	Software compatibility and internet connectivity issues; high infrastructure requirement
Shubeck et al. (36) China	Desktop-Based Virtual Reality Simulation	Knowledge, triage accuracy, attitudes toward training	Multiple-choice pre/post-tests on triage accuracy and attitude survey	Participants had more confidence in live-action training than in VR training	N/A	Participants had more confidence in live-action training than in VR training
Vincent et al. (22) United States	High-Fidelity Mannequins and Live-Action Simulation	Triage performance, learner satisfaction, self-efficacy	Electronic polling system and 5-point Likert self-assessment scale	High-fidelity manikins improved understanding of MCI triage training	N/A	Manikins couldn't simulate capillary refill or detailed neurological responses
Vincent et al. (23) United States	High-Fidelity Mannequins and Live-Action Simulation	Triage performance, self-efficacy	Observers tracked triage accuracy and timing in real-time, and Learner Evaluation Questionnaire (LEQ)	Students improved triage speed and accuracy with hands-on manikin training	N/A	Manikins relied on clothing and external markers for injury simulation

ED, Emergency Department; LEQ, Learner Evaluation Questionnaire; MCI, Mass Casualty Incident; NASA TLX, NASA Task Load Index; SP, Standardized Patient; START, Simple Triage and Rapid Treatment; SUS, System Usability Scale; VR, Virtual Reality.

Lastly, only one study (32) explored a different approach to disaster communication through text-based messaging mobile application against voice over radio, reaching improved information accuracy during hospital response to an MCI simulation.

In all these virtual environments, a variety of MCI scenarios were simulated, from urban area explosions (12, 13, 22, 23, 27, 31, 34), CBRNE events (18, 26, 29, 30), natural hazards such as earthquakes, floods and tornados (32, 36, 43, 44), mass shootings (39, 43, 44), car crashes (14, 33), and other non-specified MCIs scenarios (10, 11, 30, 41).

Measurements tools and metrics varied across studies. Most used scores, checklists, or pre/post-knowledge tests, while some conducted surveys with Likert scales. One study (18) implemented debriefing and focus group discussion to record participants experiences. Only three articles conducted follow-up assessment within their methods, completing post-test within 2 weeks, 1 month, and 2 months (10, 27, 30).

Comparative studies revealed mixed findings, highlighting either no improvement or no change in improvement in comparison to traditional methods (11, 27, 31, 33, 36, 43). For instance, while Knight et al. and Cicero et al. supported VR's superiority over traditional card-sort or lecture-based training (34, 44), others such as Shubeck et al. found participants preferred live-action training due to its perceived realism and greater emotional engagement (36). Moreover, Follman et al. highlighted a trade-off between quality and efficiency, noting that improvements in triage accuracy with augmented reality technology came at the cost of longer assessment times (31).

4 Discussion

4.1 Summary and key trends

This scoping review synthesized 32 original studies published between 2000 and 2024 that examined the use of technological tools in DM education and training. In doing so, it addressed the primary research question by mapping current evidence on how simulation technologies have been utilized to enhance knowledge acquisition, technical skills development, decision-making, and learners' engagement in disaster settings. The review also provided insights into the secondary research question by analyzing the outcome measures and evaluation strategies used to assess training impact, revealing substantial variability and lack of standardization across studies.

Mass casualty triage was the most prominent topic in the included studies and the over where digital training approaches were most actively developed. Over two-thirds of the included studies addressed triage either as the primary learning objective or as a key element of broader disaster preparedness curricula.

The reviewed studies employed a range of digital modalities to simulate mass casualty incidents and evaluate learners' ability to assess, prioritize, and manage multiple victims. These simulations commonly focused on structured protocols such as START or SALT, and measured outcomes like triage accuracy, speed, and decision-making under pressure.

4.2 Effectiveness and evaluation challenges

Although most studies reported positive short-term outcomes such as improved knowledge or triage accuracy, relatively few demonstrated statistically significant advantages of technology-enhanced methods over traditional pedagogical approaches such as lectures, tabletop exercises, or live-action simulations. Several studies, particularly those comparing VR with traditional simulations, found no significant differences in performance outcomes (27, 33, 43). Moreover, some participants expressed a preference for live-action scenarios, citing higher perceived realism and emotional engagement (36).

Despite the growing interest in simulation technology for DM education, our review found that the evaluation of training effectiveness remains inconsistent and largely unstandardized. Outcome measures across the included studies varied widely, with most relying on short-term knowledge quizzes, self-reported confidence, or simplified checklists. This pattern reflects what Cook et al. (7) described as a recurring challenge in digital learning environments, where the complexity of technologies often outpaces the development of appropriate evaluation frameworks, making it difficult to assess effectiveness beyond superficial metrics (42). In our review, none of the included studies employed structured tools, and only a few used validated instruments or follow-up assessments (30, 41). Several factors may explain this gap, including the lack of disaster-specific evaluation frameworks (46), and practical constraints that favor the use of simple, low-resource assessment methods over validated, behavior-based instruments (47).

At the same time, the increased reliance on simulation-based training is not unique to disaster medicine. Virtual reality and other immersive technologies are being increasingly adopted across health professions education, showing promising results in areas such as cardiopulmonary resuscitation and emergency care training. As highlighted by Trevi et al., simulation is emerging as both an effective and cost-effective modality in broader clinical education contexts (48). This further underscores the urgency of developing robust, transferable evaluation strategies that can be adapted across disciplines and scenarios, including but not limited to disaster response training.

These findings are consistent with those of Voicescu et al. (49), who reported a widespread mismatch between the educational objectives of disaster management programs and the strategies used to evaluate their outcomes. While many programs aimed to develop applied competencies these were often measured using basic tools that capture only surface-level cognitive gains. Our review reinforces this observation in the context of technology-enhanced training: although many interventions sought to build operational triage capabilities or situational awareness through immersive or interactive modalities, their impact was typically assessed using low-resolution, knowledge-based instruments.

4.3 Simulation fidelity and integration

Previous research indicated that simulation fidelity—the extent to which and educational environment replicates real-world conditions—plays an important role in shaping learning outcomes (50). Across several studies in our review, participants reported that immersive VR and high-fidelity simulation environments improved their engagement, emotional involvement, and ability to make rapid triage decisions under pressure (13, 16, 38). These tools commonly provided real-time feedback, sensory immersion, and dynamic scenarios that stimulated the cognitive and emotional challenges of mass causality incidents, supporting faster decision-making and triage. In contrast, desktop-bases simulation and e-learning modules, while useful for foundational knowledge, were often perceived as less realistic and less helpful in preparing learners for the stress and ambiguity of mass casualty incidents (30, 43).

This difference in learner perception aligns with the broader simulation literature, which emphasize that emotional, physical, and conceptual fidelity are essential to effective experiential learning, particularly in high-stakes, team-based scenarios like disaster response. Zechner et al. (51) echoes this in their mixed reality prototype study, demonstrating that the incorporation of realistic environmental cues—such as visual distraction and situational variability—along with adaptive scenario challenges, improved participants' sense of preparedness by more closely replacing the dynamic and unpredictable nature of real–world MCIs. Chang et al. (52) similarly found that tactile feedback from a capillary refill simulator resulted in more accurate diagnostic judgments compared to video–only instruction.

Furthermore, Weinstein et al. (53) concluded that effective MCI simulation must balance high physical conceptual, end emotional fidelity. This assertion is also reflected in our review, suggesting that hybrid and multi-modal formats hold promise, even if they were only explored in a few studies (25, 31).

These converging findings suggest that the effectiveness of technology-enhanced disaster education appears to depend less on the type of technology used and more on how well it is integrated into a coherent, immersive, and learner centered training ecosystem. Rather than novelty or format alone, realism, interactivity, and scenario flexibility appear to be the key drivers of meaningful learning. As digital tools become increasingly accessible and sophisticated, the next challenge may lie in ensuring their use is aligned with clear educational goals and embedded in structured, outcome-based training programs.

4.4 Future research and practice

This review identified triage as both a central of current educational efforts and a key area for future research. Its prominence in literature and operational relevance makes it an ideal testbed for intervention studies.

Notably, no study in this review addressed the use of Artificial Intelligence (AI), Machine learning, or adaptive learning systems is DM education, despite being included in the search strategy. Further research could investigate how AI-enable platforms might support dynamic scenario generation, personalized feedback, or real-time assessment in high-pressure training environments.

To move the field forward, educators and training developers are encouraged not only to adopt emerging technologies, but to integrate them onto pedagogically sound curricula that emphasize realism., feedback, and behavioral assessment. Building on this review, our forthcoming experimental study will examine the use of a mobile application to teach triage principles to medical students using tabletop simulation design.

5 Strengths and limitations

This scoping review offers a comprehensive and timely synthesis of the literature on technology-enhanced DM education, with a specific focus on training content, modality, and outcome evaluation. The inclusion of a wide range of technologies supports a holistic understanding of the field's interdisciplinary landscape. The review also identified triage as a pedagogical priority, setting the stage for targeted intervention studies.

However, several limitations should be acknowledged. As a scoping review, this study did not include a formal appraisal of methodological quality or risk of bias in the included studies. The findings therefore reflect the breadth and distribution of available evidence rather than the strength of individual outcomes. The review was limited to English-language, peer-reviewed literature, potentially excluding relevant studies published in other languages or found in gray literature. Finally, given the rapid pace of technological innovation, it is possible that recently developed tools or training approaches may not be represented in the published literature.

6 Conclusion

This scoping review synthesized the literature on the use of technology in DM education, with mass causality triage emerging as the most frequently addressed topic. While various digital tools have shown promise in enhancing knowledge and decision making, their effectiveness remain inconsistent, and evaluation methods are often limited to short-term or self-reported outcomes.

The review highlights the importance of simulation fidelity, pedagogical integration, alignment between training goals and assessment strategies. These insights inform a future research agenda focused on evidence-based tools. As technology continues to evolve, its role in disaster preparedness must be shaped by both innovation and instructional rigor.

Author contributions

JG: Data curation, Writing – original draft, Conceptualization, Methodology, Investigation, Visualization, Software, Writing – review & editing, Resources, Formal analysis. MA: Software, Writing – review & editing, Methodology, Data curation. BA: Methodology, Data curation, Writing – review & editing, Visualization. LR: Writing – review & editing, Supervision. FB-A: Writing – review & editing, Supervision, Formal analysis. MC: Supervision, Methodology, Conceptualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

Supplementary material

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